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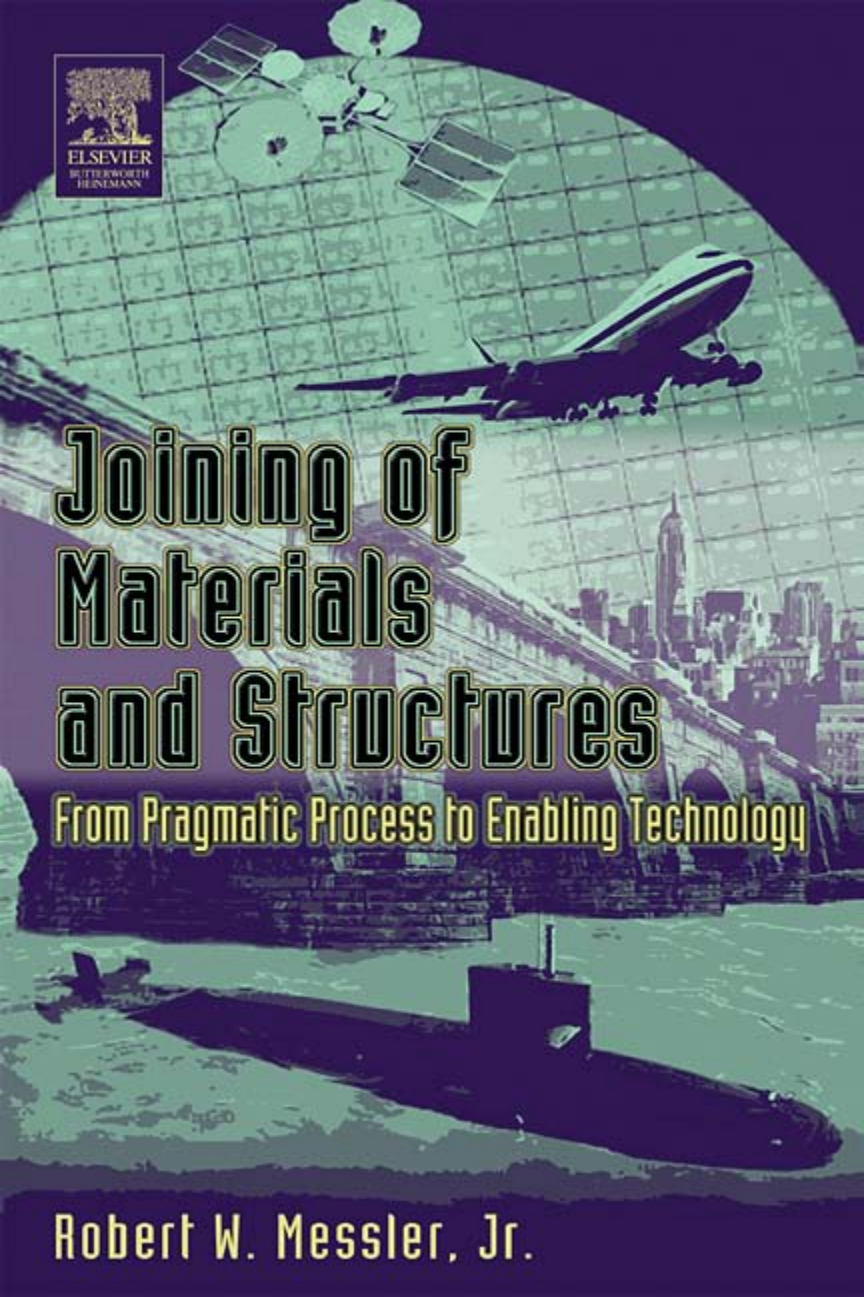
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Joining of Materials and Structures
From Pragmatic Process to Enabling Technology
Robert W. Messler, Jr.

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Preface

Joining—the process used to bring separate parts or components together to produce a unified whole assembly or structural entity—is at once the most ubiquitous, least understood, yet no less appreciated of all processes used in manufacturing. This may be because joining is often one of the last processes to be used in a complex product's manufacturing, following part shaping by casting, rolling, drawing, extrusion, forging, forming, machining, and powder compacting. In construction where joining occurs throughout the process to create the desired structure, joining is still generally underappreciated. Even in medicine—joining for the purpose of wound or surgical incision closure or repairing a bone fracture—the process is generally taken for granted.

Evidence for this lack of appreciation shows itself in two particular generic examples: engineering education and material development. In terms of engineering education, the typical undergraduate engineering curriculum in civil engineering, where structural design and construction of the built infrastructure is impossible without joining, includes only a few lectures or perhaps a short module on bolting within a course, as opposed to as even a single specialized course. The typical undergraduate curriculum in mechanical engineering, from which most structural and machine designers come, includes only a couple of hours, if that, discussing fastening. In both curricula, welding may be mentioned (although the underlying fundamentals are almost certainly not discussed), while structural adhesive bonding is virtually never mentioned. Yet each of us, every day, drives our assembled automobiles, designed by mechanical engineers over bolted or welded bridges, designed by civil engineers. When we fly, we do so in aircraft designed by aeronautical and mechanical engineers, analyzed for their stresses by civil engineers, and assembled with upwards of a million or more rivets, a significant fraction of an acre of adhesive bonds, and thousands of resistance spot welds and tens of meters of fusion welds (especially in flight-critical engines!). None of this is very comforting knowing how little time is spent learning about the process, not to mention the technology, that makes it all possible.

In terms of materials development, it is rare that one of the properties for which a new material is designed is weldability. Yet, welding is known to be used in a great deal of original equipment manufacture and even more in service repair. While considered a "mature" process with the consequence that funding for basic research is hard to come by and receipt of tenure in academia can be difficult at graduate research universities, welding problems abound. The U.S. Navy's Seawolf submarine was the subject of critical press and probing Congressional investigations because of persistent welding problems that drastically delayed its deployment and drove its costs ever upward. Aluminum–lithium alloys, seen as so attractive by aerospace companies

for their attractive strength- and modulus-to-weight advantages over conventional aluminum alloys, failed to catch on quickly because only one of the first three alloys to appear (i.e., Martin Marietta's Weldalite) was weldable and that was rather unusually by design. And then, of course, there is the tragic collapse of the catwalk over the main ballroom in the Hyatt Hotel in Kansas City due to faulty welding, the sinking of the White Star Line's unsinkable Titanic due to the brittle failure of rivets by what was supposed to be a tolerated collision with an iceberg, and the catastrophic loss of the Space Shuttle Challenger due to the failure of the O-rings used to help join and seal stages of the booster rockets.

As if all of this isn't enough evidence that we seem to know too little, or, at least, give too little thought to joining than we should, the joining challenges that we face now and into the future are growing faster than our knowledge of the process. We are, at once, designing larger and larger cruise liners and supertankers, jumbo jets and hypersonic commercial vehicles, taller skyscrapers, longer bridges (including a bridge to span the Strait of Gibraltar), and smaller and smaller hearing aids, more densely circuited CPUs, and microscopic and submicroscopic nanoscale MEMs. And even now, we are looking at the reality of rebuilding traumatized or disease-ravaged bodies through tissue engineering, where joining faces totally new challenges.

This book is being written to remedy the dearth of a comprehensive yet readable treatment of joining as not only a pragmatic process for manufacturing that we need every day, but as an enabling technology for what we will need and dream of for the future. There are few sources that discuss all of the major issues and options for joining conventional, advanced, and emerging materials, as well as large, complex structures, including the most complex material-structure of all—living tissue—and none that does so primarily from the material perspective.

This book is intended for all engineers from all engineering backgrounds, including civil, electrical, industrial, materials, mechanical, and biomedical. It is intended to be a comprehensive primer (as opposed to a comprehensive handbook), a primary textbook or collateral source for undergraduate and graduate engineering students, and a practitioner's desktop source book. Most of all, it is intended to be readable, without compromising technical accuracy and rigor. Hopefully, this book will become a reference that readers return to over and over again to refresh, reflect, and refine their knowledge and understanding.

Joining of Materials and Structures approaches the subject of joining from the material perspective but without ignoring essential issues of joint design, structural performance, practical production, economics, and service reliability. Part 1 addresses the general process, fundamental process options, and various process embodiments of joining, while Part 2 addresses the challenges posed by specific material types, combinations, and forms. Chapter 1 introduces the process of joining, describing the many and varied reasons for joining, the fundamental approaches, and the impact of loading and stress state on joint design and joining. Chapters 2 and 3 describe the use of mechanical forces for mechanical joining, including the two approaches using supplemental fasteners and integral design features. Chapters 4 and 5 describe the use of chemical forces for adhesive bonding, as well as the chemical agents to obtain adhesion. Chapter 6 describes the use of the physical forces that are ever-present between

atoms for welding materials together. Chapters 7 and 8 focus on the two major related sub-forms of welding, namely brazing and soldering, while Chapter 9 provides an overview of the essential metallurgy for welding, brazing, and soldering. Part 1 ends with Chapter 10 describing variant and hybrid joining processes—thermal spraying, braze welding, rivet-bonding, weld-bonding, and weld-brazing—as well as welding processes that are hybrids of other welding processes.

In Part 2, Chapter 11 considers the joining of metallic materials, Chapter 12 the joining of ceramic materials (including cement and concrete) and glasses, and Chapter 13 the joining of polymers. Chapter 14 considers the special challenges associated with joining materials that are composites of other fundamental materials, as well as the joining of wood, while Chapter 15 considers the too-often-ignored and often daunting challenge of joining fundamentally different materials. Part 2 ends with Chapter 16 addressing the challenges associated with joining actual structures, of all sizes, in all environments, and it addresses, for the first time in an engineering book, the joining of living tissue to other tissue or to other materials. The book ends with Closing Thoughts, in an attempt to put everything in perspective in a page or two.

A book like this just doesn't pop into one's head one day. It develops slowly over time, as the knowledge, ideas, views, and suggestions of many people are processed into what is, hopefully, a logical presentation that organizes things, ties them together, and extrapolates them into the future. There are many people to thank for their contributions; so let me thank those people:

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To my daughter Vicki and her husband, my son-in-law, Avram Kaufman, my thanks for their creativity in the earliest "joining practitioner" in Figure 1.1 and for cover art.

Most of all, I thank my wonderful wife of 30 years, Joan. No one has had to hear more complaining, listened to more anecdotes about what I was writing, put up with less than the attention she so deserves, tolerated my frequent forays to the word processor at 3 or 4 in the morning, or provided more encouragement when I was down. This book and, even more so, everything else of meaning in my life I owe to her patience and love.

Please read this book and enjoy what I think is a great process!

Robert W. Messler, Jr.
December 14, 2003

PART I

Joining Processes & Technologies

Chapter 1

Introduction to Joining: A Process and a Technology

1.1 JOINING DEFINED

From the dawn of humankind (in fact, maybe even before, if Figure 1.1 is any more than a fanciful anthropomorphism), the ability to join similar or dissimilar materials has been central to the creation of useful tools, the manufacture of products, and the erection of structures. Joining was undoubtedly one of the first, if not the first, manufacturing technology. It began when a naturally shaped or broken stone was first joined to a naturally forked or split stick; first wedging the stone into the fork or split, and later, as the first "engineering improvement" took place, lashing the stone into place with a vine or piece of animal sinew to produce a hammer, ax, or spear. This earliest creation of functional tools by assembling simple components surely must have triggered a whole rash of increasingly more complex, useful, and efficient tools, as well as an entirely new approach to building shelters from Nature's elements and from enemies. It also must have quickly advanced—or degenerated—into creative ways of producing efficient defensive and offensive weapons for war: longbows and longboats, crossbows and castles, swords and siege machines.

With the passage of time, the need for and benefits of joining have not abated; they have grown. More diverse materials were fabricated into more sophisticated components, and these components were joined in more diverse and effective ways to produce more sophisticated assemblies. Today, from a Wheatstone resistance bridge to the Whitestone suspension bridge,[1] from missiles to MEMS,[2] joining is a critically important consideration in both design and manufacture. In fact, we as a species and joining as a process are at the dawn of a new era—one in which joining changes from simply a pragmatic process of the past to an enabling technology for the future, to be practiced as much by physicists and physicians as by hard-hatted riveters and helmeted welders.

[1] The Whitestone Bridge links the boroughs of Queens and the Bronx outside of the borough of Manhattan in New York city.

[2] *MEMS* are "micro-electromechanical systems"—machines on a microscopic scale (see "MEMS" in the Index).

Figure 1.1 An artist's concept that joining, as an important process in manufacturing, began with—or maybe even before—the dawn of humankind, making it one of the oldest of all processes. (Courtesy of Victoria Messler-Kaufman, with permission.)

In the most general sense, *joining* is the act or process of putting or bringing things together to make them continuous or to form a unit. As it applies to fabrication, joining is the process of attaching one component, structural element, detail, or part to create an assembly, where the assembly of component parts or elements is required to perform some function or combination of functions that are needed or desired and that cannot be achieved by a simple component or element alone. At the most basic level, it is the joining (of materials into components, devices, parts, or structural elements, and then, at a higher level, the joining of these components into devices, devices into packages, parts into assemblies, and structural elements into structures) that is of interest here.

An *assembly* is a collection of manufactured parts, brought together by joining to perform one or more than one primary function. These primary functions can be broadly divided into the following three categories: (1) structural, (2) mechanical, and (3) electrical. In *structural assemblies,* the primary function is to carry loads—static, dynamic, or both. Examples are buildings, bridges, dams, the chassis of automobiles, or the airframes of aircraft or spacecraft. In *mechanical assemblies,* the primary function, while often seeming to be (and, in fact, also having to be) structural, is really to create, enable, or permit some desired motion or series of motions through the interaction of properly positioned, aligned, and oriented components. Examples are engines, gear trains, linkages, actuators, and so on. Without question, such assemblies must be capable of carrying loads and, therefore, must be structurally sound, but load carrying is incidental to creating or permitting motion. Finally, in *electrical*

assemblies, the primary purpose is to create, transmit, process, or store some electromagnetic signal or state to perform some desired function or set of functions. The most noteworthy examples are microelectronic packages and printed circuit boards but also include motors, generators, and power transformers. Here, too, there is also often a need to provide structural integrity, but only to allow the primary electromagnetic-based function(s) to occur.

Usually, assemblies must perform multiple functions, albeit with one function generally being primary and the others being secondary. Thus, the joints in assemblies must also support multiple functions. For example, soldered joints in an electronic device have the primary function of providing connectivity—for the conduction of both electricity and heat—but they must also be able to handle mechanical forces applied to or generated within the system. They must also hold the assembly of electrical components together in the proper arrangement under applied stresses, acceleration, motion, vibration, or differential thermal expansion and contraction. Regardless of the primary or secondary functions of an assembly and its component joints, joints are an extremely important and often critical aspect of any assembly or structure, and they are found in almost every structure. In fact, joints make complex structures, machines, and devices possible, so joining is a critically important and pervasive process (Figure 1.2, taken from the cover of this book).

At some level, joining anything comes down to joining materials, with the inherent microscopic structure and macroscopic properties of the material(s) thus dictating how joining must be accomplished to be possible, no less successful. After all, everything and anything one might need or wish to join is made of materials. Nevertheless, there surely are issues and considerations associated with joining structures that go beyond material issues and considerations.

1.2 REASONS FOR JOINING MATERIALS AND STRUCTURES

For many structures, and certainly for static structures,[3] an ideal design would seemingly be one containing no joints, since joints are generally a source of local weakness or excess weight, or both. However, in practice, there are actually many reasons why a structure might need or be wanted to contain joints, sometimes by necessity and sometimes by preference.

There are four generally accepted goals of any design (Ashby, 1999; Charles *et al.,* 1997): (1) functionality, (2) manufacturability, (3) cost, and (4) aesthetics. While one could argue about the order of relative importance of the latter three, there is no arguing about the primal importance of the first (i.e., functionality—at least if the designer is putting things in proper perspective!). Without functionality, whether something can be manufactured at all or at a low cost while looking good or even be pleasing to look at is of little, if any, consequence. It should thus come as no surprise

[3] *Static structures* are structures that are not required or intended to move. In fact, when such structures are required or intended to move, at least on any gross scale (beyond normal elastic deflection, for example), it is usually considered a failure of the structure. *Dynamic structures*, on the other hand, are intended to move from place to place or within themselves.

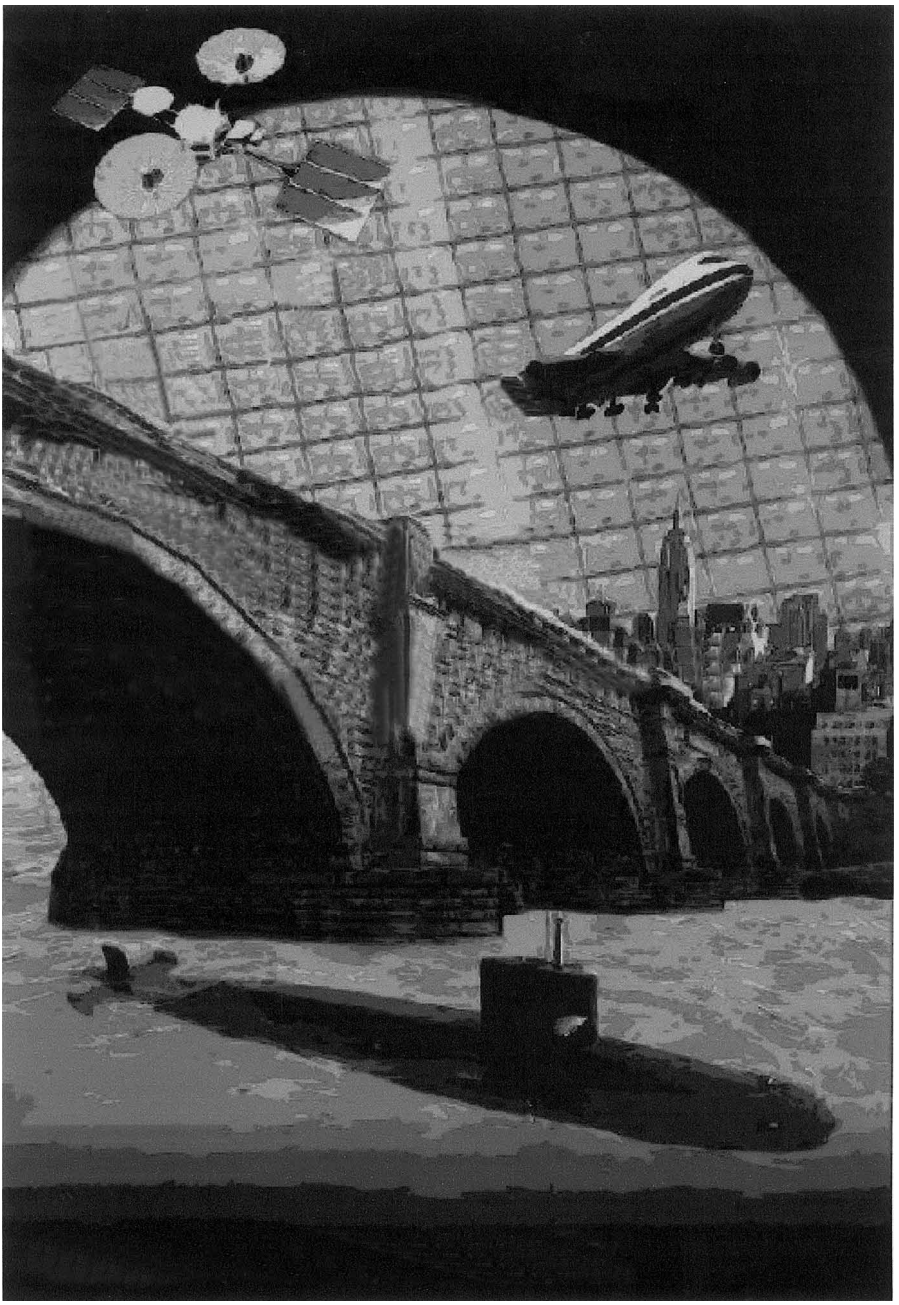


Figure 1.2 The use and importance of joining pervades our world and our lives, as shown in this depiction from the cover of this book; it enables the creation of structures from beneath the seas to the outermost regions of space, and everything in between. (Courtesy of Avram Kaufman, with permission.)

that the reasons for joining materials or structures composed of materials are directly related to achieving one or more of these four goals. Let us look at these reasons goal by goal.

If one thinks about structures (on any size scale), there are two fundamental types: (1) those that are not required, intended, or wanted to move, either from place to place or within themselves, to function, or both, and (2) those that are. The former can be referred to as *static structures,* while the latter can be referred to as *dynamic structures.* Achieving functionality in both types requires that the structural entity[4] be able to carry loads, whether applied from the outside (i.e., external loads) or generated from within (i.e., internal loads). In both types of structures, functionality depends on any and all parts responsible for some aspect of the overall function of the structure or assembly to be held in proper arrangement, proximity, and orientation. In dynamic structures, however, there is the added requirement that these component parts must be capable of needed motion relative to one another while still having the ability to carry any and all loads generated by and/or imposed on the assembly. It is immediately obvious that a dynamic structure must contain joints. If it did not, implying it was made from one piece, there could not possibly be any relative motion between parts. Hence, joining is essential for allowing relative motion between parts in a dynamic structure. Less obvious is the fact that static structures usually (albeit not always) require joints, too, and thus require joining. If a static structure is very large, however, the likelihood that it can be created from one piece decreases as the size increases.

Hence, joining is needed in large structures since such large structures (or even components of very large structures) cannot be produced by any primary fabrication process, whether these structures are static or dynamic. There is, in fact, a limitation on the size—and also the shape complexity—for any and every primary fabrication process, such as casting; molding; deformation processing by forging, rolling, or extrusion; powder processing; or lay-up and other special fabrication processes for composites. Once this primary process limitation is exceeded, joining, as a secondary fabrication process, is necessary. Figure 1.3 shows an example of the need for joining to produce large-scale structures.

Sometimes special functionality is required of a structure that necessitates joining. An example is the desire or need to see through or into or out of a sealed structure. One could make the entire structure from a transparent material, such as glass, but doing so could seriously compromise the structure's integrity for other functions, such as resisting impact loads or tolerating flexing. Hence, joining is necessary to achieve special functionality achievable only by mixing fundamentally different materials (e.g., metals and glasses in an automobile's windows). Figure 1.4 shows an example of joining for this reason.

For some products or structures, it is necessary for them to be portable (e.g., to bring them to a site for short-term use, and then be removed, often for use elsewhere).

---

[4] *Structural entity* refers to a device composed of materials (e.g., a p-n-p transistor), a package composed of devices (e.g., a logic chip), an assembly of parts or packages, or a collection of structural elements used to produce a structure (e.g., a bridge).

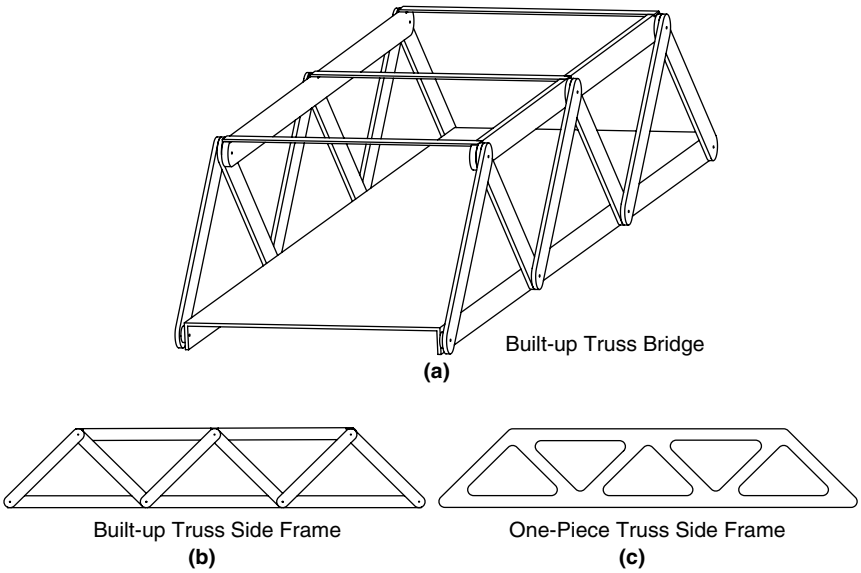


Figure 1.3 An important reason for joining is to enable the construction of objects or structures that are simply too large to fabricate in one piece by any means. Here a truss bridge (a) is assembled from pinned, riveted, or bolted elements (b), since creating the bridge from one piece (c) would be impractical, if not impossible.

Clearly, for something to be portable it either has to be small or has to be able to be disassembled and re-assembled. Examples range from temporary modular buildings for providing shelter or security to climbing cranes used in erecting skyscrapers, to huge tunneling machines such as those used to build the "Chunnel" under the English Channel between France and England. In all cases, joining—by some means that is preferably, but not necessarily, easy to reverse—is needed.

Finally, there are situations where service loads threaten a structure's integrity due to the propagation of internal damage (e.g., a crack). The tolerance of a structure to ultimate failure from a propagating flaw can be dealt with in two ways: (1) by making the structure from a material with inherent tolerance for damage (in the form of high fracture toughness, for example); and/or (2) by building crack-arresting elements into the structure (often, if not always, in the form of joints). Hence, joining can be used to impart structural damage tolerance, beyond inherent material damage tolerance. Figure 1.5 shows the superb example of built-up riveted structure in a metal aircraft airframe structure for damage tolerance.

Most of the time, the second most important goal of design is manufacturability. If a functional design cannot be manufactured at any cost, it will never have a chance to function. Joining plays a key role in achieving manufacturability in several ways. First and foremost is the use of joining to achieve structural efficiency, which clearly relates closely to functionality. Structural efficiency means providing required structural integrity (e.g., static strength, fatigue strength and/or life, impact strength or toughness, creep strength, etc.) at minimum structural weight. As an example, a fighter

Figure 1.4 Joining allows the use of fundamentally dissimilar materials to achieve special function. Here a glass windshield consisting of glass mounted in a metal frame and sealed with a polymer is being robotically assembled into a modern automobile constructed of metal, plastic, or reinforced plastic. (Courtesy of KUKA Schweissanlagen GmbH, Augsburg, Germany, with permission.)

aircraft's wing plank or cargo aircraft's floor plank in a conventional Al-alloy design can be made lightweight while still providing required structural stiffness by creating ''pockets'' in thick plates by machining or by creating built-up stiffeners (e.g., ribs and frames) by riveting. Both end up using only as much metal as is absolutely needed to carry the loads. However, building up small pieces into a structurally efficient assembly trades off increased assembly labor against wasted material (i.e., scrap) and machining time, and, as a byproduct, favorably impacts structural damage tolerance. These two approaches, both of which seek to maximize structural efficiency, are shown schematically in Figure 1.6. Obviously, the riveted assembly offers the added advantage of optimized (i.e., maximized) material utilization known as ''buy-to-fly ratio'' in the

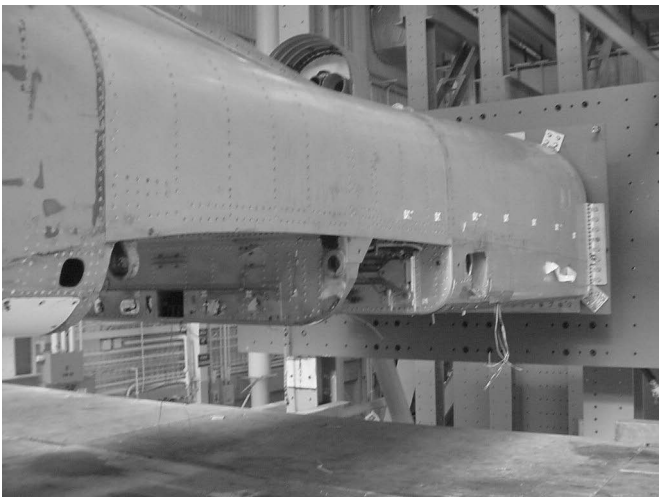


Figure 1.5 Joining one part to another can result in enhanced damage tolerance in a structural assembly over that inherent in the materials used to create the individual parts of the assembly, nowhere more apparent or important than in the riveted, built-up Al-alloy structure of an airplane. Here, the riveted fuselage of a T38 trainer is shown. (Courtesy of Northrop Grumman Corporation, El Segundo, CA, with permission.)

aerospace industry. Figure 1.7 shows a comparison between the main landing gear door of an E2C aircraft fabricated from all composite details by adhesive bonding versus all Al-alloy details by riveting, to reduce part count, virtually eliminate fasteners, dramatically reduce assembly labor (required to drill holes and install rivets), and save weight. Thus, joining offers structural efficiency and an opportunity for optimized material utilization.

Related to optimized utilization of material is optimized selection of material. Optimum functionality sometimes requires a material of construction to satisfy two opposing requirements. For example, while it is often desirable for a portion of a structure (such as the ground-engaging edge of a bulldozer blade) to resist wear by being hard, making the entire structure from a hard, wear-resistant material would compromise the structure's toughness under expected impact (e.g., with boulders). It would also make fabrication of the large and complex shaped blade, in the example of a bulldozer, terribly difficult. Using joining, it is possible to mix two different materials to achieve both goals (e.g., a wear-resistant material at the blade's ground-engaging edge and a tough material in the blade body). So, joining allows optimum material selection (i.e., the right material to be used in the right place). This could also allow an inherently damage-tolerant material to be mixed with a less damage-tolerant material using joining to achieve the aforementioned structural damage tolerance.

As mentioned earlier, large size and/or complex shape can pose a problem for certain fabrication processes and certain materials. As examples, casting allows complex shapes to be produced at relatively low cost (using simple mold-making

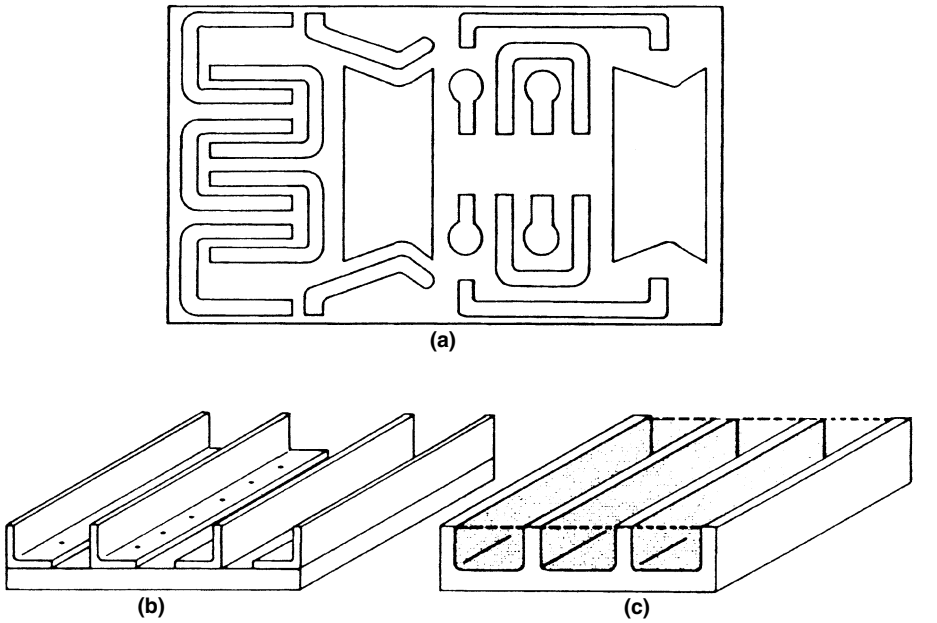


Figure 1.6 Schematic illustration showing how joining, here by fastening (b), can be used as effectively as machining (c) to achieve structural efficiency; the former by building up details, the latter by removing material (say by machining) to minimize weight and carry service loads. The need to nest parts to optimize material utilization is shown in (a). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 1.4, page 8, with permission of Elsevier Science, Burlington, MA.)

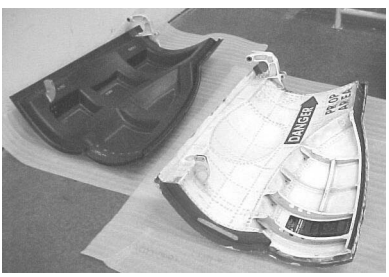


Figure 1.7 An adhesively bonded composite main landing gear door for an E2C (left) dramatically reduces part count, assembly labor, and weight compared to a conventional built-up, riveted Al-alloy door (right) for the same aircraft. (Courtesy of Northrop Grumman Corporation, El Segundo, CA, with permission.)

techniques for small-run castings or using more elaborate mold-making techniques for large-run castings), but has greater limitations on size than a forging process with its inherently more limited shape complexity capability. These can also be considered manufacturability issues, both of which can be overcome by joining.

Finally, there are many structures (e.g., all civil- or built-infrastructure structures) that must be erected, if not fully fabricated, on site. In either case (i.e., prefabricated parts shipped to the site or parts fabricated on site), joining is essential. Figure 1.8 shows a bridge that obviously had to be erected on site using prefabricated detailed parts.

Cost is often a key consideration, even if not the driver, for a manufactured product or structure. Joining allows cost to be minimized by (1) allowing optimal material selection (versus forcing compromise); (2) allowing optimal material utilization (versus forcing scrap losses); (3) keeping the weight of materials needed to a minimum (i.e., maximizing structural efficiency); (4) achieving functionality through large size and/or complex shape (without pressing primary processing limits); and (5) sometimes (depending on the process) allowing automated assembly (to reduce labor cost and improve product consistency). Figure 1.9 shows how joining can be automated, thereby lowering the cost of a product's manufacture.

Cost-effectiveness means more than low cost of manufacture, however. It also means low cost of maintenance, service, repair, and upgrade, all of which are made

Figure 1.8 Sometimes joining is necessary not only because it allows something too large or too complicated to be created from one piece to be made, but also because the structure has to be constructed or erected on site, as is clearly the case for the bolted bridge shown. In modern bridge building, pre-fabricated details are joined on site after being pre-fitted in the more controlled environment of a fabrication shop. (Courtesy of the American Bridge Company, Coraopolis, PA, with permission.)

Figure 1.9 Modern manufacturing often benefits when labor-intensive, quality-critical assembly is automated, as exemplified in the automobile industry by robotic welding. (Courtesy of DaimlerChrysler AG, Stuttgart, Germany, with permission.)

practical, beyond feasible, by joining. Finally, joining facilitates responsible disposal, whether by recycling or other means.

How a finished product looks and how it makes the user feel (aesthetics) can be enabled by joining also. From the adhesive bonding application of expensive wood veneers, to less expensive wood furniture or plastic veneers that simulate wood, to the thermal spray application of protective and/or decorative coatings, to the application of attractive architectural façades, joining is often an enabler of improved aesthetics. By allowing more complex shapes to be produced cost-effectively, joining may further contribute to aesthetics through form beyond appearance.

Table 1.1 summarizes the reasons for joining structures and the materials that comprise them.

1.3 CHALLENGES FOR JOINING MATERIALS

When one thinks about it, joining always comes down to joining materials. Whether one is erecting a concrete block wall by cementing block to block, constructing a ship by welding steel plates to one another, or implanting a titanium-alloy artificial hip joint into a sufferer of chronic and crippling rheumatoid arthritis, what is being joined is one material to another more fundamentally than one structure to another. This is most obvious in the case of implantations, where biocompatibility of the implant material is the key to successful implantation (see Chapter 16, Section 16.4.5). Hence, the real

Table 1.1 Reasons for Joining Structures and Materials (by Design Goals)

Goal 1: Achieve Functionality
• To carry or transfer loads in an array of parts needing to act together without moving (i.e., a static structure)
• To carry and transfer loads in an array of parts needing to act together by moving (i.e., a dynamic structure)
• To achieve size and/or shape complexity beyond the limits of primary fabrication processes (e.g., casting, molding, forging, forming, powder processing, etc.)
• To enable specific functionality demanding mixed materials
• To allow structures to be portable (i.e., able to be moved to or from sites)
• To allow disassembly for ultimate disposal
• To impact damage tolerance in the structure beyond that inherent in the materials of construction (i.e., structural damage tolerance)
Goal 2: Facilitate Manufacturability
• To obtain structural efficiency through the use of built-up details and materials
• To optimize choice and use of just the right materials in just the right place
• To optimize material utilization (i.e., minimize scrap losses)
• To overcome limitations on size and shape complexity from primary fabrication processes
• To allow on-site erection or assembly of prefabricated details
Goal 3: Minimize Costs
• To allow optimal material selection and use (versus forcing compromise)
• To maximize material utilization and minimize scrap losses
• To keep the total weight of materials to a minimum (through structural efficiency)
• To provide more cost-effective manufacturing alternatives (versus forcing a primary fabrication process to its limit)
• To facilitate automation of assembly, for some methods
• To allow maintenance, service, repair, or upgrade; all of which reduce life-cycle costs
• To facilitate responsible disposal
Goal 4: Provide Aesthetics
• To enable application of veneers, facades, etc., different from the underlying structure
• To allow complex shapes to be formed

challenges of joining (for any of the reasons described in the previous section) are usually directly the challenges of joining materials and usually indirectly the challenges of joining structural shapes (i.e., structures).

It is fairly safe to say that fewer parts, simpler shapes, and less-sophisticated, lower-performance materials require less elaborate joining processes and procedures. Not surprisingly, the corollary is also true (i.e., more-sophisticated, higher-performance—so-called ''advanced''—materials require special attention and more elaborate joining processes and procedures). In every case, however, the general rules are: (1) select a joining process that minimally alters or disrupts the material's inherent microstructure (including chemistry), while still achieving required or desired functionality; and (2) consider the effect of the process of joining on the resulting properties of the final material and structure.

The challenges to joining posed by materials are growing as (1) the sheer diversity of materials continues to grow (e.g., the challenge of joining ceramic-matrix composites to monolithic ceramics in advanced-concept engines); (2) the degree of "engineered" microstructure and properties of materials increases (e.g., directionally solidified eutectic superalloy gas turbine blades to monolithic superalloy rotors); and (3) designers and users demand and modern, sophisticated analysis techniques allow higher operating stresses, permit combined or complex loading, and enable combined properties for severe environments all at minimum weight, minimum cost, minimum environmental impact, and maximum flexibility. Often to meet these demands, designers combine diverse materials in individual functional elements to create hybrid structures that truly do optimize overall function, performance, and cost. An example is shown in Figure 1.10.

Clearly, the pressure on processes for joining materials is growing.

1.4 CHALLENGES FOR JOINING STRUCTURES

We live in a world where we are being pushed to—and are thus moving toward—new and extreme conditions. Bigger, faster aircraft, deeper-water offshore drilling platforms (Figure 1.11), smaller machines and microelectro-mechanical systems (or MEMS) (Figure 1.12), longer and more comfortable stays in space (Figure 1.13), greater need to extend the operating life of nuclear power plants (Figure 1.14)—all of these and more pose new challenges to our ability to join structures beyond joining materials. Bigger supertankers and petrochemical refineries demand larger and thicker-section structures be joined and be leak-tight. Offshore drilling platforms demand erection, anchoring, and periodic repair to occur underwater. The intriguing possibilities of MEMS demand micro- (if not nano-) joining. Ventures into space and the need to make repairs on radioactive nuclear reactors demand automation of joining processes heretofore operated manually. And, past successes in limb reattachment and the promise of tissue engineering make new demands that pragmatic manufacturing processes like joining become enabling technologies for biotechnology. Past lessons learned in manufacturing suggest joining must adapt and evolve to meet new demands and realize new possibilities.

Let us take a look at how joining is already changing and how it must change in the future.

1.5 HOW JOINING IS CHANGING OR MUST CHANGE

Until quite recently and, for most applications even now, joining has been a "secondary" fabrication process when classified with all other generic fabrication processes in manufacturing (Charles *et al.*, 1997). Not secondary in the sense that it is of lesser importance (although that, too, is often the thinking!), but in the sense that it occurs after parts, components, or structural elements have been fabricated by other means. Five generic process categories are usually considered primary: (1) casting; (2) molding; (3) deformation processing (using mill processes like rolling or extrusion, or

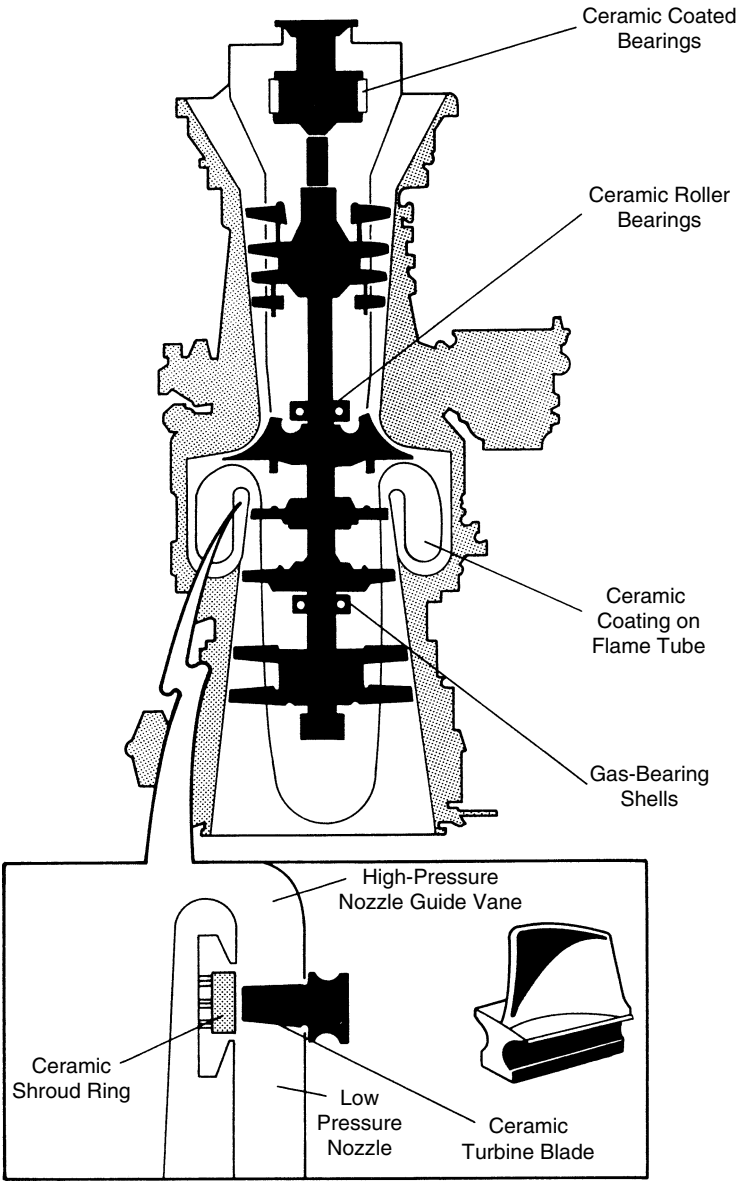


Figure 1.10 Joining makes possible the use of just the right material, in just the right amount, in just the right places to create ''hybrid structures,'' as exemplified by the schematic of an advanced ceramic engine for a helicopter. (Reprinted from *Ceramic Joining*, Mel M. Schwartz, Figure 7.1, page 167, ASM International, Materials Park, OH, with permission.)

Figure 1.11 Larger and larger drilling platforms for use in deeper water require extensive welding during their construction, erection, and maintenance and repair. (Courtesy of Bechtel Corporations, San Francisco, CA, with permission.)

other processes like forging or sheet-metal forming); (4) powder processing; and the catch-all (5) special processing, which is epitomized by processes used for fabricating items from polymer-matrix composites (e.g., broad-good and tape lay-up, filament winding, weaving, etc.). Being primary, these processes either create the starting stock (e.g., rough casting, rolled plate, forged billet or rough forging, powder preform, etc.), or they produce a part to near-net shape (e.g., investment casting, injection molding, precision forging, pressed-and-sintered part, etc.). Most of the time, joining is one of the later, if not the last, steps in a product's manufacture. And, worse yet, it is often an afterthought; examples include alloys that are not designed to be welded being used in products or structures needing welding, using add-on screws to back up integrally snap-fit plastic assemblies to prevent accidental disassembly, and applying a bolted reinforcement (or "band-aid") over a weld repair on a cast-iron machine frame.

This is beginning to change and must continue to change for joining to achieve its full potential and to have its full impact. The best examples are in microelectronics, where semiconductor devices (e.g., MOSFETs) are created by synthesizing the p- and n-type extrinsic semiconductor materials as integral device elements in a single device. Material synthesis, device or part synthesis, and assembly or system synthesis occur in an integrated, even if not simultaneous, fashion. This trend must—and will—continue, making joining an integral part of primary processing.[5]

[5] By the way, there are already examples where welding is being used to produce finished or near-net shapes, as will be described later in Chapter 10 under "Hybrid Welding Processes" and under the topic of "Shape Welding" (see the Index).

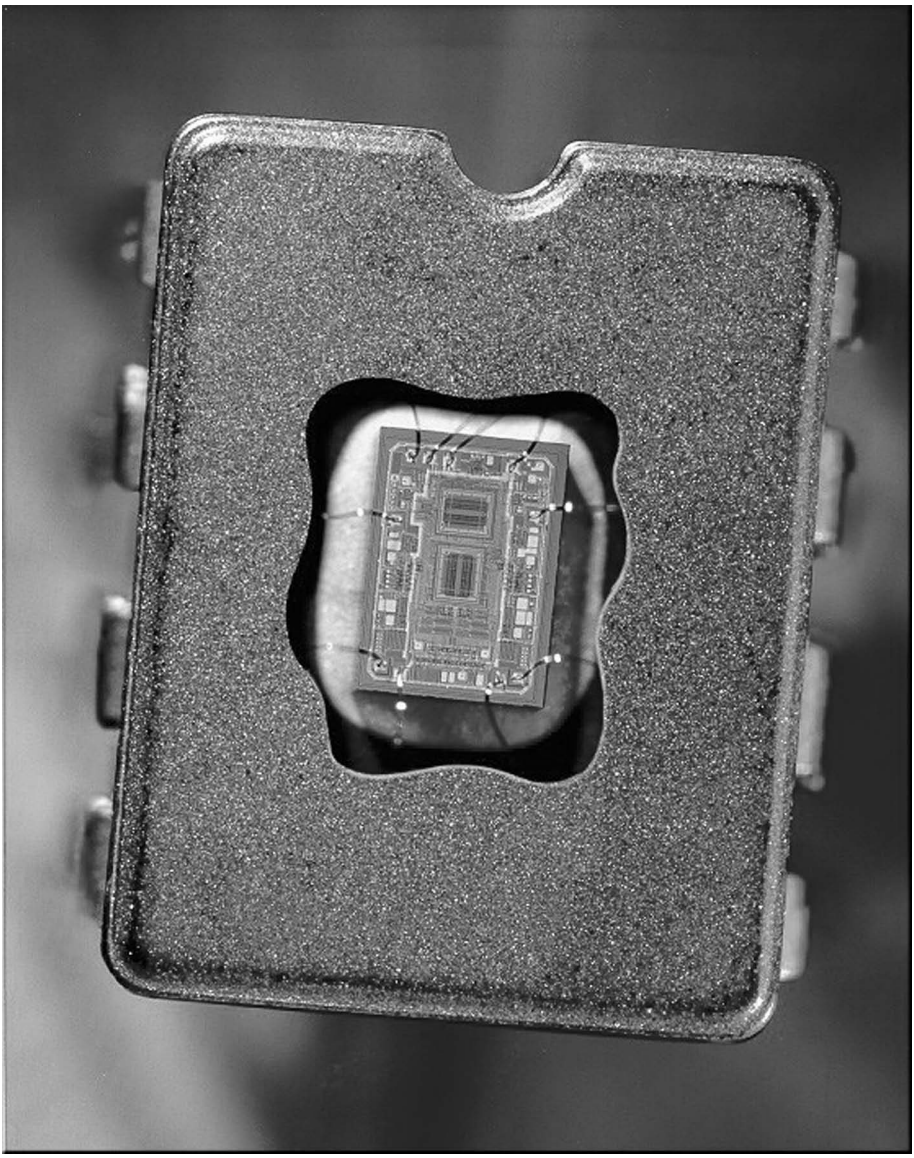


Figure 1.12 Special joining techniques and methods are needed to enable micro-electro-mechanical systems (MEMS) to be assembled. In this cut-away sample, various micron-scale details have been joined to create an accelerometer through the use of a silver-filled glass to bond the die to the ceramic package base, ultrasonic aluminum wire bonds between aluminum bond pads on the die and Alloy 42 lead frame, and use of a glass frit to seal the package lid to the package base. (Courtesy of Analog Devices, Inc., Cambridge, MA, with permission.)

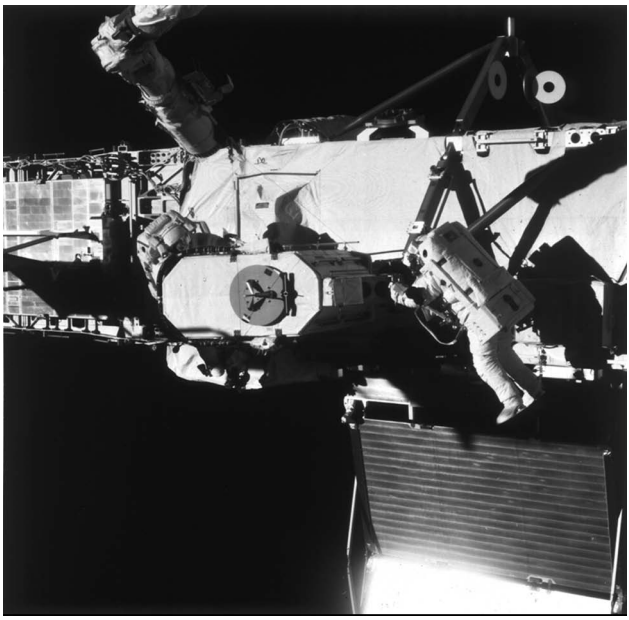


Figure 1.13 Allowing humans to work, learn, and live at the edge of outer space is made possible in the Orbiting International Space Station by many types of joining, including mechanical fastening, snap-fit assembly, and welding. (Courtesy of the National Aeronautics and Space Administration, Washington, DC, with permission.)

One only has to look at news releases or technical briefs in present-day materials or manufacturing journals to see terms like "self-forming joints," "self-limiting joining," "self-healing materials," and "self-assembling structures" to sense the change of joining from a secondary to a primary process. Self-forming joints can be found in microelectronics when lean Cu-Al or Cu-Mg alloys are sputtered onto SiO_2-coated Si substrates and heat-treated to create a bond-forming Al_2O_3 or MgO joint layer. In this same process, such joint formation can be made self-limiting by carefully controlling the composition and amount (i.e., thickness) of the sputtered alloy. The quest in the military aerospace industry for self-healing or self-repairing of damaged skins or understructures now reveals a technical and practical reality using nanotechnology. Encapsulated resins and catalysts in the form of nanoparticles can be embedded in thermosetting polymer-matrix composites to affect automatic "healing" of any flaws that develop and rupture the encapsulants in the process of the flaw's propagation. And, finally, self-assembly of microscale (or eventually nanoscale) components into MEMS (or eventually NEMS) is being employed by carefully designing the shapes of the components to enable and assure that they can be "shaken" into proper arrangement and orientations.

A second major change that is occurring, and must continue to occur, is accepting joining as a value-adding, not a value-detracting, process. While it surely is accepted in some instances, it is not in far too many other instances. Designers and

Figure 1.14 Joining is essential to the routine scheduled maintenance and unscheduled emergency repair, not only the construction, of nuclear power plant components; it sometimes demands that welding, for example, be done using either mechanized systems operated by welders outside of radioactive areas or by remotely controlled robots within such areas. (Courtesy of Bechtel Corporation, San Francisco, CA, with permission.)

process engineers must accept high-cost joining (often arising from high labor intensity and/or high-priced labor) for high-value applications and highly valued benefits. The best example might be heeded by those charged with joining continuous, unidirectional-reinforced composites for demanding service by watching surgeons reattach a severed limb. First, patience, time, and precision are accepted costs for the high value to be gained. Second, joining begins with the critical internal structure (analogous to the reinforcements in composites) and ends with the less critical external structure (analogous to the matrix of composites). Bones and blood vessels (as essential structural elements) are joined, followed by muscles and tendons and ligaments (as actuators), followed by nerves (as sensors). After all these critical elements have been joined, the surrounding tissue and skin are joined (as analogues to the matrix of the composite). Think of this when the joining of composites is discussed near the end of this book, in Chapter 14.

Figure 1.15 shows how precision microjoining is accepted in microelectronics manufacturing to obtain highly valued hermeticity.

Finally, joining must continue to change from a pragmatic process in fabrication, as much an afterthought and a necessary evil as a value-adding step in manufacturing, to an enabling technology. Microelectronics could not have achieved what is has without joining as a technology enabling solid-state devices. The future of information technology will be enabled by microelectronics and nanoelectronics, optoelectronics,

Figure 1.15 Joining has already become a more integrated part of the synthesis of materials, devices, and systems in microelectronics, where microjoining is used to hermetically seal critical electronic packages. (Courtesy of International Business Corporation, Poughkeepsie, NY, with permission.)

photonics, and molecular electronics (called "moletronics"), and joining will enable these to act as a technology, not simply as a process. Likewise, much of the tremendous promise of biotechnology (e.g., gene splicing, tissue engineering, and the like) will also depend on joining as a technology more than as a pragmatic process.

1.6 JOINING OPTIONS

1.6.1 Fundamental Forces Involved in Joining

Joining is made possible by the following three—and only three—fundamental forces: (1) mechanical forces, (2) chemical forces, and (3) physical forces, which have their origin in electromagnetic forces. Not coincidentally, these three fundamental forces are, in turn, responsible for the three fundamental methods or processes by which materials and structures can be joined: (1) mechanical joining, (2) adhesive bonding, and (3) welding.

Mechanical forces arise from interlocking and resulting interference between parts, without any need for chemical or physical (electromagnetic) interaction. As shown in Figure 1.16, such interlocking and interference can (and to some extent always does) arise at the microscopic level with surface asperities[6] giving rise to friction or, at macroscopic levels, using macroscopic features of the parts being joined. Chemical forces arise from chemical reactions between materials. Such reactions can take place entirely in the solid state of the materials involved or can take place (often much more rapidly, uniformly, and completely) between a liquid and a solid phase of the materials involved, relying on wetting of the solid by the liquid. Finally, the naturally occurring attraction between atoms, oppositely charged ions, and molecules leads to bond formation and joining due to physical forces in what is generally referred to as welding. Brazing and soldering are special subclassifications of welding, that find their origin and effectiveness in the combined effects of chemical and mechanical forces (albeit with the strength of the ultimate joints, in both sub-classifications, arising from the physical forces of atomic bonding). Unlike adhesive bonding, neither brazing nor soldering, nor welding for that matter, is dependent upon chemical forces to produce joint strength. They depend just on physical forces.

Table 1.2 summarizes how different fundamental forces give rise to the different joining options.

Let us look at each of these major joining options.

1.6.2 Mechanical Fastening and Integral Attachment: Using Mechanical Forces

Mechanical fastening and integral mechanical attachment are the two ways in which mechanical forces can be used to join structures, rather than materials. Together,

[6] *Asperities* are the "peaks and valleys" found on all real surfaces, regardless of efforts to make the surface smooth.

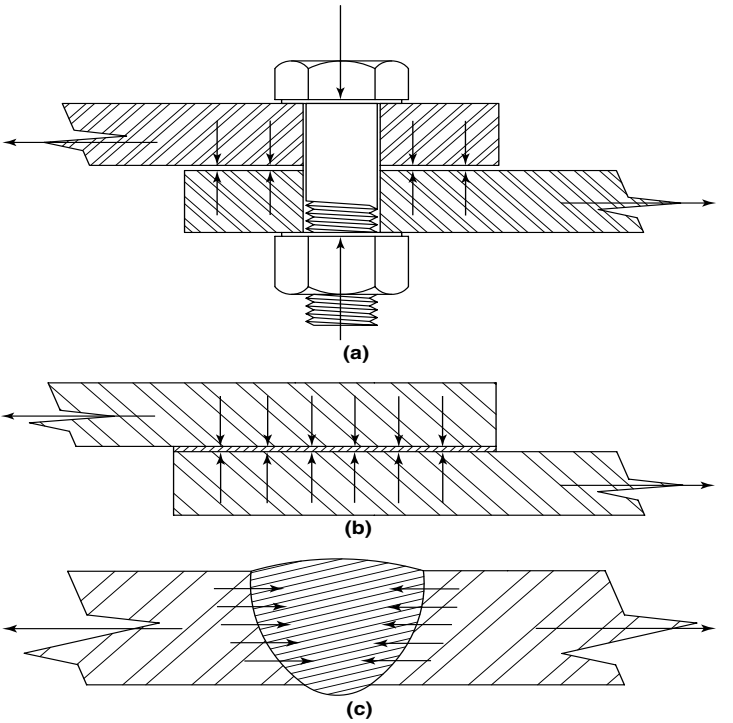


Figure 1.16 A schematic illustration of the various forces used in joining materials and structures: (a) mechanical forces for fastening, (b) chemical forces for adhesive bonding, or (c) physical forces for welding.

mechanical fastening and integral mechanical attachment constitute what is properly known as *mechanical joining.* In both methods, joining or attachment is achieved completely through mechanical forces, arising from interlocking—at some scale—and resulting physical interference between or among parts. At the macroscopic level, interlocking and interference arise from designed-in or processed-in (or, in nature, from naturally occurring) geometric features. In *mechanical fastening,* these features are the result of the parts being joined and a supplemental part or device known as a "fastener." The role of the fastener is to cause the interference and interlocking between the parts, which, by themselves, would not interlock. In integral mechanical attachment, on the other hand, these interlocking features occur naturally in, are designed in, or are processed into the mating parts being joined.

Figure 1.17 shows a typical mechanically fastened structure, while Figure 1.18 shows a typical integrally attached structure using snap-fit features.

In both mechanical fastening and integral mechanical attachment, interlocking and interference also arise at the microscopic level in the form of friction. Friction has its origin in the microscopic asperities—or "peaks and valleys"—present on all real surfaces, regardless of the effort to make these surfaces smooth. Not only do these asperities interfere and interlock with one another mechanically, but also, under the right

Table 1.2 Fundamental Forces Used in Different Joining Processes, Sub-Processes, Variants, and Hybrids

	Primary	*Secondary*
Mechanical Joining		
Mechanical Fastening	Mechanical	–
Integral Attachment	Mechanical	–
Adhesive Bonding		
Using Adhesives	Chemical	Mechanical/Physical
Solvent Cementing	Chemical	Physical
Cementing/Mortaring	Chemical	Mechanical
Welding		
Fusion Welding	Physical	–
Non-fusion Welding	Physical	–
Brazing	Physical	Chemical (Reaction)
Soldering	Physical	Chemical (Reaction)/ Mechanical
Variant Processes		
Braze Welding	Physical	Chemical (Reaction)
Thermal Spraying–Metals/Ceramics	Physical*	Mechanical/Chemical (Reaction)
Thermal Spraying–Polymers	Chemical*	Mechanical
Hybrid Processes		
Rivet-Bonding	Mechanical/Chemical	–
Weld-Bonding	Physical/Chemical	–
Weld-Brazing	Physical	Chemical (Reaction)

*If done correctly!

circumstances (e.g., adhesive wear or abrasion) with the right materials (e.g., metals), atomic bonding actually can and does occur. Localized "welding" of asperities by these naturally occurring physical forces causes metal transfer manifested as "seizing."

Common examples of mechanical fasteners are nails, bolts (with or without nuts), rivets, pins, and screws. Less well recognized, but still common, mechanical fasteners are paper clips, zippers, buttons, and snaps (actually "eyelets and grommets"). Special forms of mechanical fasteners are staples, stitches, and snap-fit fasteners. Common examples of designed-in integral mechanical attachments are dovetails and grooves, tongues-and-grooves, and flanges, while common examples of processed-in attachments are crimps, hems, and punchmarks or "stakes." A common use of friction for mechanical joining is roughened or "knurled" mating (or faying) surfaces, as in Morse tapers (see Chapter 3).

The principal advantage of all mechanical joining (with the sole exception of some processed-in features) is that it uniquely allows intentional relative motion (i.e., intentional movement) between mating parts. It also rather uniquely allows intentional disassembly without damaging the parts involved. Regrettably, this major advantage can also be a major disadvantage (i.e., the ability to intentionally disassemble can lead to

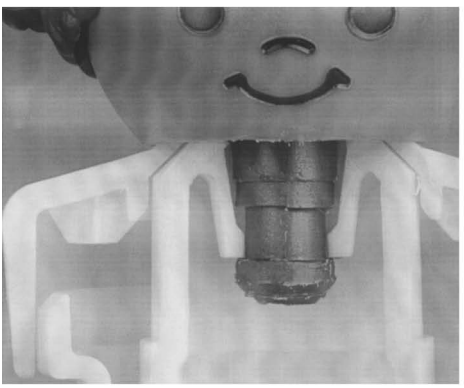
Figure 1.17 Floor trusses are typically mechanically fastened to the vertical structure of modern skyscrapers using high-strength bolts and nuts, such as those shown here in the Quaker Tower, Chicago, IL. (Courtesy of Bechtel Corporation, San Francisco, CA, with permission.)

unintentional or accidental disassembly if special care is not exercised). More will be said about the relative advantages and disadvantages of mechanical joining processes in Chapter 2.

Mechanical fastening and, to a lesser extent, integral mechanical attachment can be used with any material, but is best with metals and, to a lesser extent, with composites. Problems arise in materials that are susceptible to damage through easy (especially ''cold'') deformation (such as certain polymers under high point loads) or fracture by stress concentration at points of mechanical interference due to poor inherent damage tolerance (such as brittle ceramics and glasses). Problems also arise in materials that are susceptible to severe reductions in strength or damage tolerance in certain directions due to anisotropy (such as in continuous, unidirectionally reinforced composite laminates through their thickness). Another great advantage of all mechanical joining is that, since it involves neither chemical nor physical forces, it causes no change in the part's or material's microstructure and/or composition. This makes it possible to join inherently different materials mechanically.

Specific problems associated with mechanical joining of specific materials will be discussed in Chapter 2 of this book.

(a)



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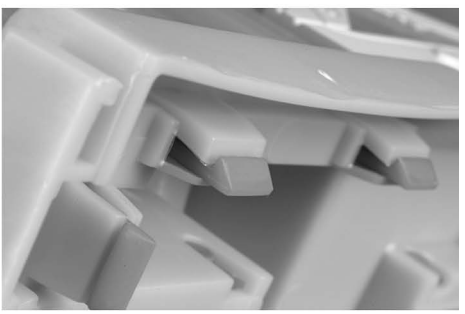


(c)

Figure 1.18 Children's toys are commonly assembled from molded plastic parts using integral ''snap-fit'' attachment features to avoid using screws and other small objects that children can put in their mouth and choke on. In this Little People Farm™ set (a), cantilever hooks and catches (b) and annular post snaps (c) are used. (Courtesy of Fisher-Price Corporation, East Aurora, NY, with permission.)

1.6.3 Adhesive Bonding: Using Chemical Forces

In adhesive bonding, materials and the structures they comprise are joined one to the other with the aid of a substance capable of holding those materials together by surface attraction forces arising principally (but not usually solely) from chemical origins. The bonding agent, called an "adhesive," must be chemically compatible with and chemically bondable to each substrate of what are called "adherends." Sometimes actual chemical reactions take place that give rise to the bonding and "adhesion," while more often no actual reaction is involved, just the development of surface bonding forces from other sources such as adsorption or diffusion. In such cases, adhesion arises from chemical bond formation, usually (but not always) of a secondary type (e.g., van der Waal's, hydrogen, or Loudon bonding). Occasionally, chemical bonding is aided and abetted by contributions from mechanical interlocking (i.e., mechanical forces) and/or physical forces (e.g., electrostatic forces).

Depending on the nature of the adhesive chosen and the adherends involved, adhesive bonding usually causes little or no disruption of the microscopic structure of the parts involved, but it may cause varying (but usually minor) degrees of chemical alteration or disruption. Because attachment forces arise and occur over the surfaces of the parts being joined, loads that must be carried and transferred by the joint are spread out or distributed so that no stress concentrations (like those found at the points of actual fastening or attachment in mechanical joining) arise. The greatest shortcoming of adhesive bonding is the susceptibility of adhesives, particularly those that are organic as opposed to inorganic in nature, to environmental degradation. More will be said about the relative advantages and disadvantages of this joining process later, in Chapter 4.

Metals, ceramics, glasses, polymers, and composites of virtually all types, as well as dissimilar combinations of these, can be successfully adhesive-bonded. Disassembly can occasionally be accomplished, but never without difficulty and seldom without causing some damage to the parts involved.

Figure 1.19 shows the use of adhesive bonding in the airframe structure of a modern aircraft.

1.6.4 Welding: Using Physical Forces

Welding is in many respects the most natural of all joining processes. It has its origin in the natural tendency of virtually all atoms (except those of the inert gases), all oppositely charged ions, and all molecules to form bonds to achieve stable electron configurations, thereby lowering their energy states. In practice, *welding* is the process of uniting two or more materials (and, thereby, the parts or structures made from those materials) through the application of heat or pressure or both to allow the aforementioned bonding to occur. Figure 1.20 shows a typical application of welding employing an electric arc as a heat source to construct a ship from pre-fabricated (also welded) modules.

The terms "welding," "welding processes," and "welds" commonly pertain to metallic materials. But it is possible—and it is the practice—to also produce welds in

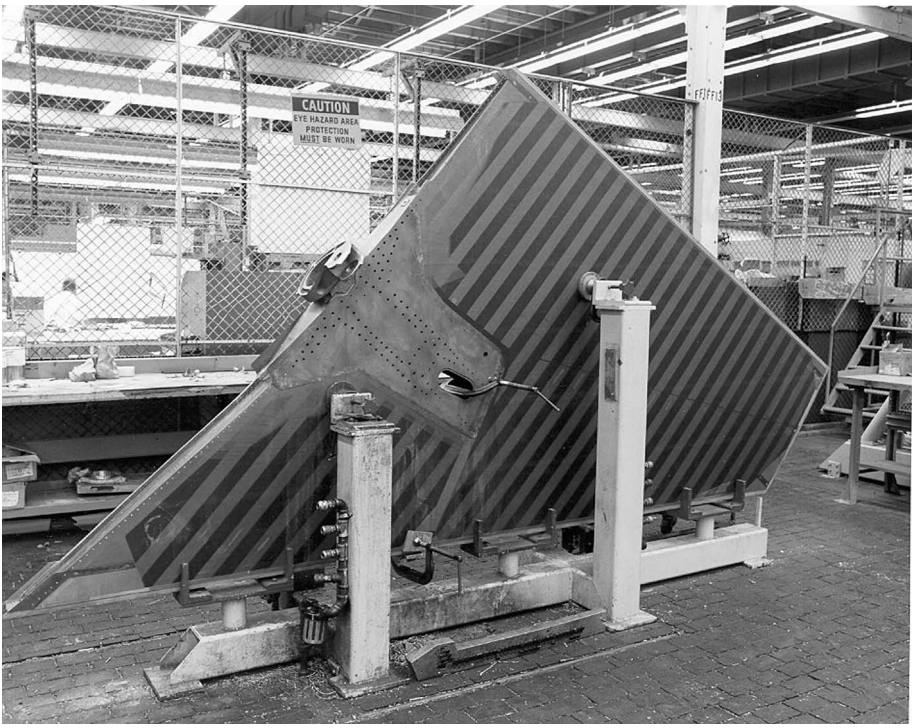


Figure 1.19 Adhesive bonding is used in the assembly of the airframes of modern aircraft, especially when thermoplastic or thermosetting polymer-matrix composites are employed as they are here on the hybrid thermosetting epoxy–graphite/epoxy–boron and titanium-alloy horizontal stabilizer of the F14 fighter. (Courtesy of Northrop Grumman Corporation, El Segundo, CA, with permission.)

certain polymers (i.e., thermoplastics) and glasses and, to a lesser extent, in some ceramics. Welding of composite materials can be accomplished to the degree that it is possible and acceptable to join only the matrix, as the process is performed today. By definition for a process that must form primary bonds to accomplish joining, welds cannot be produced between fundamentally different types or classes of materials (e.g., metallic-bonded metals to ionic- or covalent-bonded ceramics).

The relative amount of heat or pressure or both required to produce a weld can vary greatly. This is, in fact, one of the great advantages of this joining process—versatility through a vast variety of process embodiments. There can be enough heat to cause melting of two abutting base materials to form a weld with very little pressure beyond what is needed to simply hold these materials in contact. When this is the case, the process is known as ''fusion welding.'' Alternatively, there might be little or no conscious or intentional heating, but with enough pressure to cause some degree of plastic deformation (commonly called ''upsetting'' if it occurs on a macroscopic scale and friction or creep if it occurs on a microscopic scale), welds can be produced. In any case, melting or fusion is not required to establish primary bonds; only pressure

Figure 1.20 Ships of all kinds are fabricated by welding small parts into large parts, large parts into structural modules, and modules to one another to construct the hull and superstructure. Here, a larger pre-fabricated modular section of the hull of the carrier USS Reagan is shown being lifted into place for welding to the rest of the hull. (Courtesy of Northrop Grumman Corporation's Newport News Shipbuilding, Newport News, VA, with permission.)

is required to cause large numbers of atoms (or ions or molecules) to come into intimate contact. Such processes are known as "solid-phase welding" or "non-fusion welding" or, if the pressure is significant, "pressure welding."

Not surprisingly, because primary bonds are formed during joining, welding results in extremely strong joints per unit area, so it is often the process of choice for particularly demanding high-load/high-stress applications. Welding is described in detail in Chapters 6 and 7.

There are two subclassifications of welding in which the base materials are heated but *not* melted, a filler material is added and melted, and little or no pressure is applied; the molten filler spreads to fill the joint by capillary attraction forces. These two, known as *brazing* and *soldering,* are described next.

1.6.5 Brazing: A Subclassification of Welding

Brazing is a subdivision or subclassification of welding in which the materials comprising the joint are heated to a suitable temperature in the presence of a filler material having a liquidus temperature[7] above 450°C (840°F) and below the solidus temperature(s) of the base material(s). This allows flow of the molten filler under the action of wetting and capillary attraction forces. Bonding is accomplished without melting and

[7] The *liquidus temperature* is the temperature at which an alloy, which melts over a range as opposed to at a discrete temperature, becomes completely (100%) liquid on heating. The *solidus temperature* is the temperature at which an alloy just begins to melt to form liquid on heating. On cooling, the liquidus is where the first solid appears, while the solidus is where the last liquid disappears to leave it 100% solid.

mixing the substrate materials, making possible the joining of dissimilar base materials, so long as each can form primary bonds with the filler. The filler material (usually a metal, but possibly a ceramic or glass) is caused to distribute between close-fitting, intentionally gapped joint element faying surfaces. Bonding occurs by the formation of primary bonds—metallic in metals and ionic or covalent or mixed in ceramics. In brazing, joint strength tends to also depend fairly significantly on interdiffusion between the filler and the substrate(s).

Figure 1.21 shows a typical brazed assembly. Brazing is described in detail in Chapter 8.

1.6.6 Soldering: A Subset of Brazing

Like brazing, *soldering* is a subdivision or subclassification of welding. Also like brazing, soldering requires a filler material that melts and substrates that do not melt. It is distinguished from brazing by the fact that the filler's liquidus temperature is below (not above) 450°C (840°F). As in brazing, the filler material (which is almost always a metal but can be a glass for some joining applications), or "solder," is distributed using surface wetting, capillary action, and surface tension, sometimes causing the molten solder to flow between close-fitting, intentionally gapped joint elements and sometimes simply letting the solder wet a joint element and "self-form" a smooth transitioning joint.

Figure 1.21 Brazing is used to assemble various superalloy components of a gas turbine engine, such as this vane section. (Courtesy of The General Electric Company's Aircraft Engine Division, Evansdale, OH, with permission.)

In soldering, because of the lower temperatures involved, the joining can be the result of some combination of primary (e.g., metallic or covalent) bonds and mechanical interlocking. The mechanical interlocking is sometimes itself the combination of interlocking at a macroscopic and a microscopic scale. It is macroscopic when "pigtail" leads are folded under circuit boards or behind terminal strips after the lead is passed through a hole or "via." Microscopic interlocking, of course, results from the solder interacting with the substrate's surface asperities.

As in brazing (although less than 20 years ago it was not recognized), successful soldering also requires some degree of dissolution of the substrate(s) and interdiffusion between the molten filler and the substrate(s).

Figure 1.22 shows typical mass-soldered joints in a microelectronic assembly or printed circuit or wire board. Soldering is described in detail in Chapter 9 of this book.

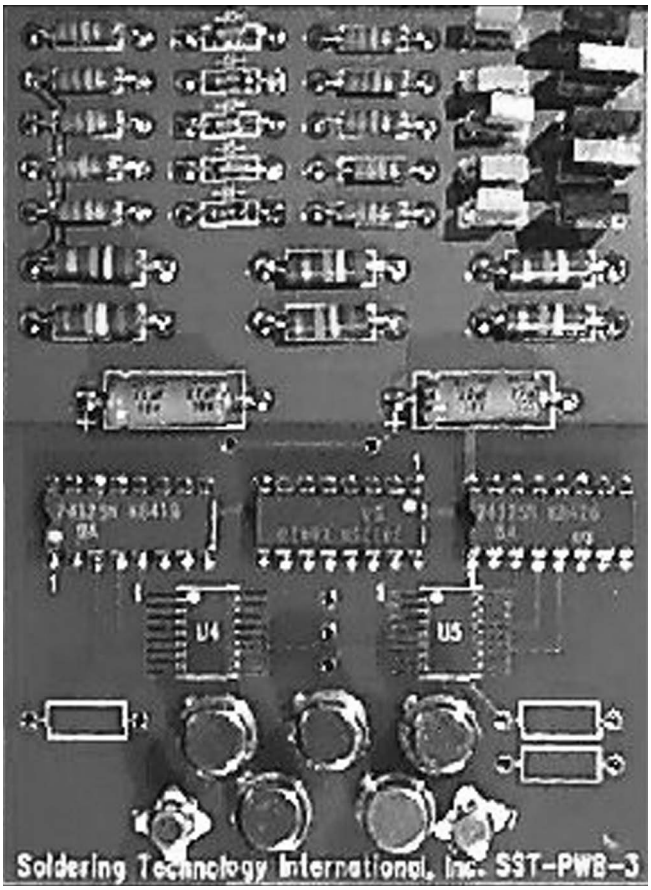


Figure 1.22 Soldering is the process of choice for producing self-shaping soldered joints en masse in the microelectronics industry. Here, rather conventional through-hole and modern surface-mount technology soldered joints are shown on a printed circuit board. (Courtesy of Sandia National Laboratory, Albuquerque, NM, with permission.)

1.6.7 Variant and Hybrid Joining Processes

While mechanical joining, adhesive bonding, and welding are the fundamental processes for joining materials and structures, and brazing and soldering are subclassifications of welding, there are some processes that are either variants or hybrids of these.

Two variants of welding are (1) *braze welding* and (2) *thermal spraying*. *Braze welding* uses a low-melting, braze-like filler material to fill a pre-prepared joint without relying on capillary action but still relying on wetting and dissolution of the substrate(s) without their melting. Hence, the process looks something like welding and something like brazing but is neither hide nor hair! Thermal spraying, often considered a variant of welding, has some characteristics of adhesive bonding in some applications. It is a special means of applying solid or softened (but rarely fully molten) material to an always solid substrate. It is often not used to join parts, but rather to simply join the material as a coating to the substrate. There are applications, however, where the process is actually used to join parts. Figure 1.23 shows thermal spraying being employed to join a coating to a substrate.

There are three examples of what are really "hybrid" joining processes in which two fundamental joining processes are combined (i.e., used together) to create some synergistic benefit(s). These three are as follows: (1) *rivet-bonding,* (2) *weld-bonding,* and (3) *weld-brazing*. In addition to these hybrids between fundamental processes, there are some hybrids between specific welding processes, to be described in Chapter 10 of this book.

Variant and hybrid joining processes are described in detail in Chapter 10.

1.7 SOME KEY CONCEPTS RELATING TO JOINTS

1.7.1 Joint Loading or Stress State

How a structure is loaded determines its *stress state,* and the stress state or the complexity of loading in a structure is critical to its performance. From the material's standpoint, the state of stress determines the point at which the material will yield (i.e., from Von Mises's or Treska's yield criteria, for example), and how able the material will be to respond in a ductile rather than brittle manner. The state of stress on a joint in a structure is also critically important in selecting an appropriate joining method or process.

Figure 1.24 schematically illustrates the progressively more severe stress states of uniaxial stress, biaxial stress, and triaxial stress. It also shows how combined loading from tension or compression, bending, torsion, and internal or external pressure in a closed cylinder gives rise to a severe stress state in the cylinder's wall (biaxial if the wall is relatively thin, triaxial if the wall is relatively thick).

As a general rule, the more complex the loading, the more complex the stress state, all else (e.g., structural geometry) being equal. Hence, the greater the demands on a given joint, the poorer the performance to be expected. Biaxial loading is more severe than uniaxial loading, and triaxial loading is more severe than biaxial loading. However, the effect of stress state complexity is much greater for some forms of joining than

Figure 1.23 Thermal spraying, which is a variant of welding in some manifestations and of adhesive bonding or brazing in others, can be used for creating shapes as well as for applying coatings (as shown here). (Courtesy of Foster-Wheeler Corporation, Perryville/Clinton, NJ, with permission.)

for others. Stress state complexity and its effects are described in detail in any good reference on mechanical behavior of materials (Dieter, 1991).

For a welded joint, the stress state does not matter very much as long as the weld filler metal's solidified structure is reasonably nondirectional (thus exhibiting isotropic

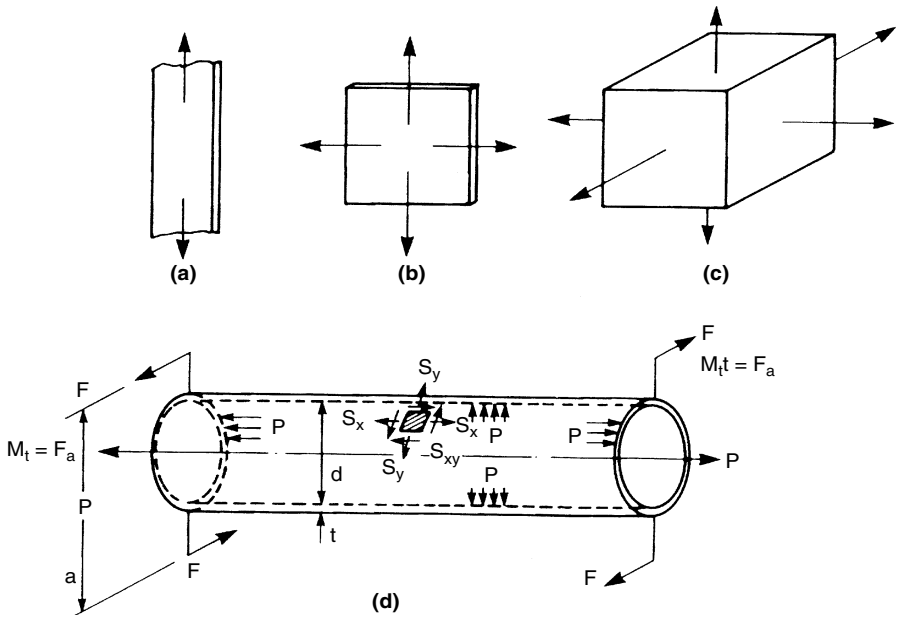


Figure 1.24 A schematic illustration of the various states of stress that can arise in structural joints: (a) uniaxial tension, (b) biaxial tension, (c) triaxial tension, and (d) complex loading from combined internal pressure and external torsion. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 1.13, page 22, with permission of Elsevier Science, Burlington, MA.)

properties) and as long as the volume of weld metal is reasonable and fairly three-dimensional. For some alloys, welding processes, welding operating parameters, and joint configurations, however, one or the other or both of these conditions are not met, and anisotropic properties result. This can lead to serious problems if loading and stress state are complex. For adhesive bonded joints, on the other hand, it is critically important to keep the state of stress as near to perfect shear as possible because the thin layer of adhesive usually performs badly under out-of-plane peel or cleavage loading. Brazed and soldered joints exhibit similar but less dramatic behavior, since these processes also employ thin layers of filler with little ability to tolerate strain through the filler's thickness. In mechanically fastened or integrally attached joints, how well the joint tolerates different stress states depends greatly on the particular fastener or attachment feature employed. Actually, the selection of a particular fastener, a fastener over an integral attachment, or a particular attachment feature depends greatly on the type of loading to be endured.

1.7.2 Joint Load-Carrying Capacity Versus Joint Efficiency

The first step in designing a joint in a structural assembly is to consider the magnitude as well as the complexity of the load(s) to be carried or transferred. The load that the joint must carry is the same as the load being carried by the structural elements on each side of

the joint for simple joints but can be higher for more complex joints composed of more than two joint elements. After thinking about the load(s) to be carried, the designer considers the stress, or the load-per-unit-cross-sectional area, in each structural element to be sure that this stress does not exceed the allowable stress for the material used in each of the elements. At this point, the designer must also consider the stress in the joint.

The *joint stress*[8] is determined by dividing the load in the joint by the effective cross-sectional or load-bearing area of the joint. The effective joint area, in turn, depends on the type of joint or joint design (e.g., straight- versus scarf-butt joints or single- versus double-lap joints), the size or dimensions of the joint, and the joining method, since the method of joining directly determines how much of the joint is really carrying loads. For welded, brazed, soldered, or adhesively bonded joints, the effective joint area is almost always the same as the area of the faying surfaces (assuming continuous, full-penetration welding, or continuous full-area brazing, soldering, or

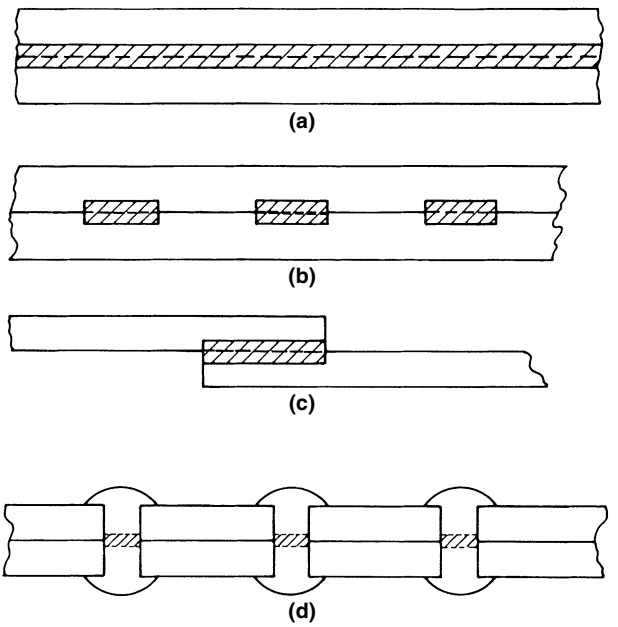


Figure 1.25 A schematic illustration showing how different joining processes result in different "effective load-carrying areas" and, thus, efficiencies for: (a) continuous welding, (b) intermittent or skip welding, (c) adhesive bonded, brazed, or soldered, and (d) riveted joints. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 1.11, page 18, with permission of Elsevier Science, Burlington, MA.)

[8] The *joint stress* as defined here is different from the stress in the joint section. The stress in the joint section is simply the load carried by the joint divided by the effective area of the structure at the joint. For fastened joints, this is the area of the structural element minus the area of the fastener holes along some plane cutting through the joint. The *joint stress*, on the other hand, would be the load carried by the joint divided by the load-bearing cross-sectional area of fasteners or welds along some plane cutting through the joint.

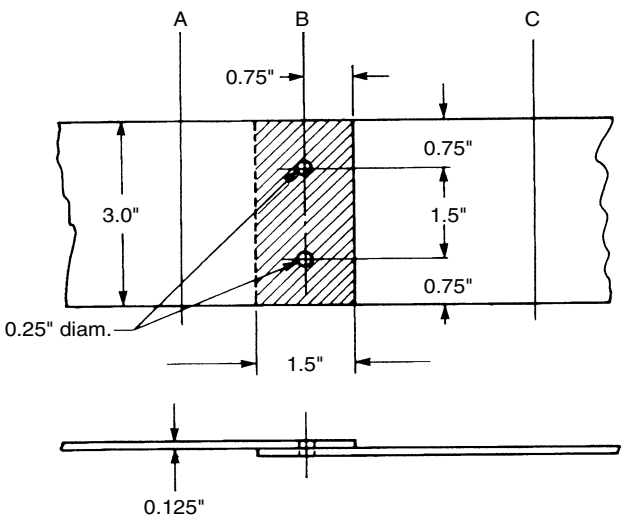
adhesive bonding). For mechanically fastened or integrally attached joints, the effective area is almost always much less than the area of the joint faying surfaces, and is given by the cross-sectional area of all of the fasteners or attachments used in making the joint. The actual points of joining or attachment are virtually never continuous. Brazing, soldering, and adhesive bonding, on the other hand, are almost always continuous, while welding can be continuous or discontinuous (or intermittent). Welding may be continuous when sealing against fluid leaks is required, and can be either continuous or discontinuous when welds are strictly to carry loads, with continuous welds being used when loads become larger.

Figure 1.25 schematically illustrates the effective area of various joints, including continuous and discontinuous welded joints, as well as brazed, soldered, and adhesively bonded joints, and various fastened and integrally attached joints.

Illustrative Example 1.1—Calculation of Joint Stress.

For the single-overlap joint shown in Figure IE 1.1, the use of two $\frac{1}{4}$-in. diameter rivets is compared to the use of a structural adhesive applied over the full $1\frac{1}{2}$-in. overlap. The actual stress (in tension) in the joint elements for an 1,800-lb. force at planes A or C is:

$$\sigma_{A\ (or\ C)} = 1,800\ \text{lbs.}/(3.0\ \text{in.})(0.125\ \text{in.}) = 4,800\ \text{lbs/in}^2\ \text{or psi.}$$



IE 1.1 A schematic illustration of a fastened versus adhesively bonded single-overlap joint. Sections at A and C pass through the joint elements with their full cross-sectional area. Section B passes through the overlap area where, if fasteners requiring holes are needed, the cross-sectional area is reduced by the total area occupied by the holes. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 1.12, page 19, with permission of Elsevier Science, Burlington, MA.)

The actual stress (in shear) in the rivets and, alternatively, in the adhesive are:

$$\tau_{\text{rivets}} = 1,800 \text{ lbs.}/(2)(\pi)[(0.250 \text{ in.})/2]^2 = 18,355 \text{ psi}$$

and

$$\tau_{\text{adhesive}} = 1,800 \text{ lbs.}/(1.5 \text{ in.})(3.0 \text{ in.}) = 400 \text{ psi.}$$

The much lower stress carried in shear in the adhesive joint than in the structural elements carried in tension is due to the much greater area of the adhesive bond than of the element's cross-section. Likewise, the much higher stress carried in shear in the rivets than in the structural elements carried in tension is due to the much smaller area of the rivets' combined cross-sections compared to the cross-section of the structural elements. Because of this effect of effective load-carrying area, lower strength adhesives can be compared favorably to the much higher strength fasteners in total load-carrying capacity.

It is critical that a joint be able to carry imposed loads successfully. However, there are ways to get a joint to be able to carry imposed loads that cause the joint to be unacceptably heavy. For example, the joint could be made heftier (e.g., by using a thicker section at the location of a weld or by doubling the depth of overlap of an adhesive bond). The true measure of a joint's structural effectiveness is thus whether it can safely carry the loads imposed, but the ultimate efficiency of the structure, in terms of its overall load-carrying capacity, its size, and its weight, is dependent on the efficiency of the joints making up the structural assembly. *Joint efficiency* is a measure of the effectiveness of the joint compared to the rest of the structure for carrying the design or service loads, and is defined by:

$$\text{Joint efficiency} = \frac{\text{Joint stress}}{\text{Stress in the structure} \times 100\%} \tag{1.1}$$

Joint efficiency varies widely depending on the joining process or method used, and can range from very low values (say 10%) to over 100%. Some examples will help to illustrate this point.

For two pieces of metal containing a continuous, full-penetration straight-butt weld whose composition is the same as the base metal, the joint efficiency is typically 100%. That is, the strength of and stress developed in the weld itself are typically equal to the strength of and stress developed in the base metal structural elements containing the weld. A 100% joint efficiency could reasonably be considered to be a characteristic of a perfect joint. But, it is possible to have joint efficiencies that are higher or lower than 100%. If a filler metal is used that is weaker than the base metal(s) adjacent to the weld, and the section thickness of the weld is the same as that of the adjacent base metal(s), the joint efficiency will have to be less than 100% if the allowable strength of the weld is not to be exceeded. If, on the other hand, a stronger filler metal is used, the joint efficiency could exceed 100%, but to load this stronger weld to its allowable strength limit would over-stress the adjacent base metal(s). In fact, the purpose of using a higher-strength filler is to keep the stress in the weld below 100% of the allowable stress for the filler when the joint elements are loaded to their design limit.

Obviously, the effective load-bearing area in a joint has an extremely strong effect on the joint's efficiency; with small effective areas leading to high efficiencies (as with mechanical fasteners, integral attachment features, and spot or intermittent or "skip" welds) and large effective areas leading to low efficiencies (as with adhesive bonded, brazed, or some continuously soldered joints).

Welded joints exhibit efficiencies of less than 100% for one of two major reasons: (1) the weld is over-designed (i.e., is longer in length or is caused to be larger in cross-section than the adjacent structural elements by creating positive reinforcement at the weld crown and root or by placing the weld in a locally thicker section or land), or (2) the weld filler metal is of lower inherent strength than the base metal(s) (i.e., it is said to be "under-matched"). Suffice it to say here, oversized welds are (or "over welding" is) done to provide a measure of added safety, to make a structure containing welded joints be more forgiving, while "undermatched" filler may be used to force the weld to fail before the rest of the structure, acting like a "safety valve." An example of the former is often the welding found on pressure vessels, while an example of the latter is found in the use of spot welds in automobiles to absorb energy of a crash to protect the vehicle's occupants. More reasons for these choices will be described in Chapter 6 of this book.

Welded joint efficiencies typically range from approximately 50% to 100%, due to the degrading effects of the heat of fusion welding on either weld filler metal or immediately surrounding base metal properties, but they can be made to exceed 100%, as just explained. Brazed and soldered joints typically exhibit efficiencies lower than 100% (often much lower!) due to the typical use of lap (versus butt) joints and the use of lower melting (and, hence, inherently less strong) filler alloys. As service temperatures are increased, and brazed or soldered joints are loaded while at high fractions of their homologous temperatures,[9] joint efficiencies must be low at room temperature. Adhesive bonded joints can exhibit widely varying joint efficiencies, largely depending on the design intent in terms of the ultimate acceptable location of the failure (i.e., in the adhesive or in the adherends) and the adherend. For bonded polymers, joint efficiencies often approach 100%, while for bonded metals or ceramics, joint efficiencies are usually quite low (say 10–20%). What makes all of these low joint efficiencies tolerable is that the joints can still have high load-carrying capacity as a result of the large effective bonded area.

Mechanically fastened and some integrally attached joints also tend to exhibit high joint efficiencies, often exceeding 100%. In these joints, high efficiency is obtained by using fasteners made from higher strength materials than the joint elements are made of. This is done to compensate for the relatively low effective joint area associated with points versus areas of joining. Obviously, this approach (i.e., to use different materials) is impossible for integral attachments.

It should be recognized that all discussion on joint efficiency has been for statically loaded joints at room temperature. Obviously, dynamic loads (e.g., impact, fatigue), extreme temperature (e.g., well into the creep regime for materials involved),

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[9] *Homologous temperature* refers to temperature as a fraction of a material's absolute melting temperature, in degrees Kelvin.

or aggressive corrosion environments must also be taken into account. Thus, one could and should assess joint efficiency in terms of other appropriate properties, like fatigue strength, fracture toughness, and creep or stress-rupture strength.

Table 1.3 summarizes the joint efficiencies in terms of static strength, typically obtained for various joining methods in various materials.

Illustrative Example 1.2—Calculation of Joint Efficiency.

The stress in the structural elements at the planes at A or C in Illustrative Example 1.1 is:

$$\sigma_{\text{element}} = \text{Load}/\text{Area}_{\text{element}} = 1,800 \text{ lbs.}/(3.0 \text{ in.})(0.125 \text{ in.}) = 4,800 \text{ psi.}$$

The stress in the rivets, carried in shear, and in the adhesive, also carried in shear, were calculated in Illustrative Example 1.1 as $\tau_{\text{rivets}} = 18,355$ psi and $\tau_{\text{adhesive}} = 400$ psi.

Thus, the joint efficiencies for the riveted configuration versus the adhesive-bonded configuration are:

$$\text{Joint efficiency for rivets} = 18,355 \text{ psi}/4,800 \text{ psi} \times 100\% = 375\%$$

while

$$\text{Joint efficiency for adhesive} = 400 \text{ psi}/4,800 \text{ psi} \times 100\% = 8.3\%.$$

Table 1.3 Typical Achievable Joint Efficiencies for Various Processes in Various Materials in Terms of Static Strength (as a Percentage)

Joining Method	*Metals*	*Ceramics*	*Glass*	*Polymers*	*Composites*
Mechanical Fastening	75–100+	<50	<50	50–100	50–100
Mechanical Attachment	75–100+	near 100	N/A	100+	50–100+
Adhesive Bonding					
Organic adhesive	<20	<20	<20	40–100+	20–60 (100+)*
Inorganic adhesive	N/A	50–100+	20–50+	N/A	50+
Cement/Mortar	N/A	50–100+	N/A	N/A	50–100+**
Welding					
Fusion processes	50–100+	30–80	100	100	about 50
Non-fusion processes	100	80–100	N/A	100	about 50
Brazing	40–90	20–70	N/A	N/A	about 50
Soldering	5–20	<20	10–40	N/A	UNK
Braze Welding	50–75	N/A	N/A	N/A	UNK
Thermal Spraying					
Metals/Ceramics	30–80	30–80	N/A	N/A	N/A
Polymers	<20	<20	N/A	50–100+	>50
Rivet-Bonding	75–100	N/A	N/A	100+	UNK
Weld-Bonding	25–75	N/A	N/A	100+	UNK
Weld-Brazing	50–80	N/A	N/A	N/A	UNK

N/A = Not applicable (generally)
UNK = Unknown for the process
* With wood
** With cement or concrete

Obviously, the effective load-bearing area in a joint has a profound effect on the joint's efficiency, with small effective areas leading to high efficiencies and large effective areas leading to low efficiencies. Joints that are fastened with rivets or bolts tend to have high efficiencies, while joints that are bonded, brazed, or soldered tend to have low efficiencies. What matters is whether the joint, however it is made, can carry the required loads safely. Joint efficiency tends to affect the weight added to a structural assembly by the joint, with more weight added when low-efficiency joints are employed.

SUMMARY

The need for and the ability to join materials into components and structural elements and components and elements into assemblies and structures began with the dawn of humankind. From deep below the oceans to deep into space, from the information highway that is built upon microelectronics to the vehicles that ply the superhighways, joining pervades our world and our lives. The reasons for joining abound, with goals of achieving functionality, facilitating manufacturability, minimizing cost, and obtaining aesthetics, pretty much in that order. The ability to join allows products and structures to be created with sizes and shapes and performance unattainable in single pieces of a single material, and overcomes the limitations of primary fabrication processes (like casting, molding, forging, powder processing, and composite lay-up) and single material properties. First and foremost, joining allows static structures to remain static and dynamic structures to perform needed motions. Joining also allows both the choice of material and its utilization to be optimized. It imparts enhanced structural damage tolerance while improving structural efficiency. It allows service and maintenance and upgrading, and it facilitates ultimate disposal. But, none of this comes without challenges from the materials being joined as well as from the structures themselves. And all of it is forcing this age-old pragmatic process to also evolve to become an enabler for the future offered by information technology and biotechnology.

Using only three fundamental forces with their origin in mechanical interlocking and interference, chemical reactions, and atomic-level bonding, three fundamental options of mechanical joining (including fastening and integral attachment), adhesive bonding, and welding (including the subclasses of brazing and soldering) emerge. Each has its own advantages and disadvantages. Together, along with some variants (braze welding and thermal spraying) and hybrids (rivet-bonding, weld-bonding, and weld-brazing), these joining processes provide extraordinary diversity and capability. All require an understanding of the stress state to be tolerated by the resulting joint to provide structural integrity with structural efficiency. And, as will be seen in the second part of this book, all require careful consideration of the materials being joined because, when all is said and done, joining of structures is the joining of materials.

QUESTIONS AND PROBLEMS

1. Define the term *joining* in your own words.
2. What are the three major types of assemblies or structures, and what is the primary function of each? Give two examples of each type of assembly or structure in which there is essentially no other function than the primary function.
3. Give some examples of assemblies or structures with multiple functions. What are these functions? Which is (are) primary, and which is (are) secondary? Can an assembly or structure really have more than one primary function? Explain and give an example.
4. What are the four major goals of all design? Explain each goal and why it is important in manufacturing. Give an example of a design that places a preponderance of value on each of the four goals you identify.
5. For each design goal in Problem #4, give two reasons why joining is necessary or useful.
6. How can joining be used to render a structure that is more damage tolerant, even if the materials comprising the structural elements or components are not inherently damage tolerant? Give an example of this possibility using mechanical fastening, adhesive bonding, and welding.
7. What are the three fundamental forces that enable joining of materials and/or structures, and what is the origin of each force that allows joining to take place?
8. Modern manufacturing speaks of the desirability of ''net-shape'' or ''near-net-shape'' processing methods. The most common examples of such processing methods are casting, molding, certain deformation processing (e.g., forging), powder processing, and certain special processes particularly amenable to composites (e.g., tape lay-up). Explain how joining methods can be used for net-shape or near-net-shape processing, giving at least one example each for mechanical fastening, integral (mechanical) attachment, adhesive bonding, and welding.
9. What are three special challenges associated with the joining of so-called ''advanced'' materials? Give an example of each.
10. What are some special challenges posed to joining by the structure itself independent of the materials involved? Give an example of each.
11. Explain why brazing and soldering are logically considered sub-classifications of the fundamental process of welding. Differentiate brazing from fusion welding, and soldering from brazing, in the most meaningful way.
12. Define what is meant by a ''variant joining process,'' and name the two principal examples. Suggest a logical or known application of each.
13. Define what is meant by a ''hybrid joining process,'' and name the three principal examples. Suggest a logical or known application of each.
14. Define what is meant by a ''hybrid structure,'' and explain how joining is especially useful for producing such structures. Give a couple of modern examples from your experience.

15. Each specific joining process has relative advantages and shortcomings, if not disadvantages. What is the predominant advantage and what is the predominant shortcoming or disadvantage of each of the following?
    a. Mechanical fastening relative to all other processes
    b. Adhesive bonding relative to mechanical joining
    c. Adhesive bonding relative to fusion welding
    d. Fusion welding relative to brazing and soldering
    e. Brazing or soldering relative to fusion welding
    f. Brazing relative to adhesive bonding
    g. Soldering relative to brazing
    h. Brazing relative to soldering
    i. Braze welding relative to fusion welding and to brazing
    j. Weld-bonding relative to adhesive bonding and to spot welding.
16. Explain why a biaxial stress state is a more severe stress state than a uniaxial stress state, and why a triaxial stress state is the most severe of all. (Hint: consider the yield criteria for a ductile metal.)
17. Explain what limits the load-carrying capacity of a joint. Give two ways that loading capacity can be increased.
18. How would you calculate the joint efficiency of a joint required to function at elevated temperatures such as those found in operating gas turbines in aircraft? Based upon your answer, how would the efficiencies of joints produced by brazing compare to those produced by fusion welding using a filler alloy matching (i.e., of the same composition as) the base alloy?
19. A single-lap joint between two pieces of 50.0-mm-wide by 2.5-mm-thick aluminum alloy has a 25.0 mm overlap and contains four 2.5-mm-diameter aluminum alloy rivets arranged along a line, on 10.0 mm centers, with the first and last rivets located 10.0 mm from opposite edges of the joint pair. Calculate the shear stress in the rivets (i.e., the joint stress) for a unidirectional 8,800 N load applied along the longitudinal (i.e., long) centerline of the aluminum joint elements. What is the joint efficiency for this joint? Assume the following for the aluminum alloy: $\sigma_f = 470\,\text{MPa},\ \tau_f = 320\,\text{MPa}$.
    Bonus: What is the net tensile stress in the aluminum joint elements along the line of rivets?
20. For the joint in Problem #19, calculate the stress in the joint if, instead of being riveted, the joint were brazed over the entire area of the overlap. What is the joint efficiency for this case? Assume the shear strength of the braze filler is 120 MPa and the tensile strength is 180 Mpa.
    Extra: What is the net tensile stress in the elements at the midpoint of the overlap?
21. What would be the stress in the brazed joint in Problem #19 if the joint configuration were a straight-butt rather than a single-overlap joint (i.e., the two pieces of aluminum were simply butted end to end)? What would be the joint efficiency for this case?
22. Of simple tension, simple compression, simple shear, bending, and torsion, which would cause the least problem with adhesive-bonded joints? Rank all of these loading types from least problematic to most problematic.

23. How do you think riveted joints might respond to the types of loading given in Problem #22? Would you change your answer for joints that were bolted using nuts and bolts?
24. Calculate the load in a pinned assembly of four structural elements (e.g., trusses) that come to a single pinning point (one from the left and one from the right on the same horizontal line, and one each coming into the pinning point at 45-degree downward angles from the left and the right) if a 10,000 lb. load is hung from the pinning point. How does the load in this case compare to the load in each structural element?
25. A 37.5-mm-wide pair of aluminum alloy AA5754 strips, 1.0 mm thick each, are to be overlapped and adhesive-bonded using a structural adhesive with a tensile shear strength of 24 MPa. How much overlap can there be if the bonded assembly is to fail just in tensile shear (not in tensile overload) in either of the aluminum alloy strips? Assume the following: Tensile strength of AA5754 = 240 MPa; WHERE IS THE REST?

CITED REFERENCES

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Chapter 2

Mechanical Joining

2.1 INTRODUCTION

Without question, the oldest method used by humankind to join components together involved purely mechanical means—that is, it was *mechanical joining*. From the first primitive tool or weapon (we really don't know!) which had a stone wedged into a forked stick and later was lashed with a strip of plant or animal fiber (e.g., a vine or a sinew, respectively), through the first time a stone or wood wheel was locked onto a wooden axle by a wooden peg, to the assembly of modern jet airliners with nearly a million rivets and nuts and bolts in each, mechanical joining has been critical to engineering and manufacturing. The detailed methods by which mechanical joining is accomplished have expanded, the number of joints produced continues to grow, and the performance demands and expectations are becoming greater. The oldest joining process remains the most prolific, pervasive, and important joining process.

In this chapter the assembly process of mechanical joining is defined. The two manifestations of this process, *mechanical fastening* and *integral mechanical attachment*, or simply integral attachment, are described and differentiated. The numerous and sometimes unique advantages, as well as relative shortcomings and outright disadvantages, are described. The sources and types of loaded joint (i.e., *shear-loaded joints* and *tension-loaded joints)* and their subtypes are described in terms of the design analysis required and performance that can be expected. Some attention is given to the important and complicated subject of bolt and joint preloading, including determination of the appropriate level, methods of achieving the desired level, and causes of loss in service. Various factors that affect fastener and joint performance in service are presented. Finally, the seemingly new (but actually ancient) and dramatically expanding approach of employing integral designed- and processed-in (or naturally occurring) geometric features for accomplishing attachment without fasteners is discussed and described.

Actual fasteners, fastening methods, and integral mechanical attachment features and methods are described in Chapter 3.

2.2 MECHANICAL JOINING AS AN ASSEMBLY PROCESS

2.2.1 General Description of Fastening Versus Integral Attachment

Mechanical joining involves the attachment of components in an assembly (or elements in a structure) through the use of either an integral feature of the components (or elements) or through the use of a supplemental device called a "fastener," resulting in *integral mechanical attachment* and *mechanical fastening,* respectively. In both manifestations of mechanical joining, loads are transferred from one component or element to another strictly through the development of purely mechanical forces arising from the interlocking and resulting interference (or vice versa) of two or more components, or component(s) and fastener(s). At the macroscopic level, it is the geometric shapes that interact, interlock, and interfere with unwanted movement or motion, including disassembly. At the microscopic level, it is the ever-present asperities (i.e., "peaks and valleys") on real surfaces that interact, interlock, and interfere. In all cases there is no dependence on the development of any primary or secondary atomic, ionic, or molecular bonds between the components' materials.[1] This fact allows components fabricated from fundamentally different materials to be joined, since there is no need for chemical or physical interaction. In fact, if such interactiont occurs it is usually seen as problematic (e.g., galvanic corrosion or galling and seizing during adhesive wear). Like other joining processes, mechanical joining is used to create assemblies or structures from detailed parts or structural elements. Also, like any process, mechanical joining and its two subtypes exhibit both advantages and disadvantages when compared to other methods of joining.

Figure 2.1 schematically illustrates mechanical fastening versus integral attachment.

2.2.1 Advantages and Disadvantages of Mechanical Joining

Mechanical joining offers many advantages over the other fundamental joining processes, some of which make it unique. These advantages, as well as some shortcomings and outright disadvantages, are summarized in Table 2.1 and are described in detail in this section.

First and foremost, mechanical joining is unique in that it is primarily dependent on the structures being joined, and only secondarily dependent on the materials of which these structures are composed. No bonds need to be formed to accomplish joining, nor do any need to be broken to accomplish disassembly. Hence, except for a few exceptions,[2] mechanical joining methods or techniques uniquely allow simple and practical disassembly without damaging the parts involved. Disassembly is useful and frequently essential for the purposes of portability, access for maintenance or service,

[1] Actually, some incidental bonding may occur locally in some materials (like metals and plastics), giving rise to friction.

[2] The exceptions are most of the "formed-in" features that accomplish attachment (e.g., crimps, hems, stakes, folded tabs, etc.). See Chapter 3.

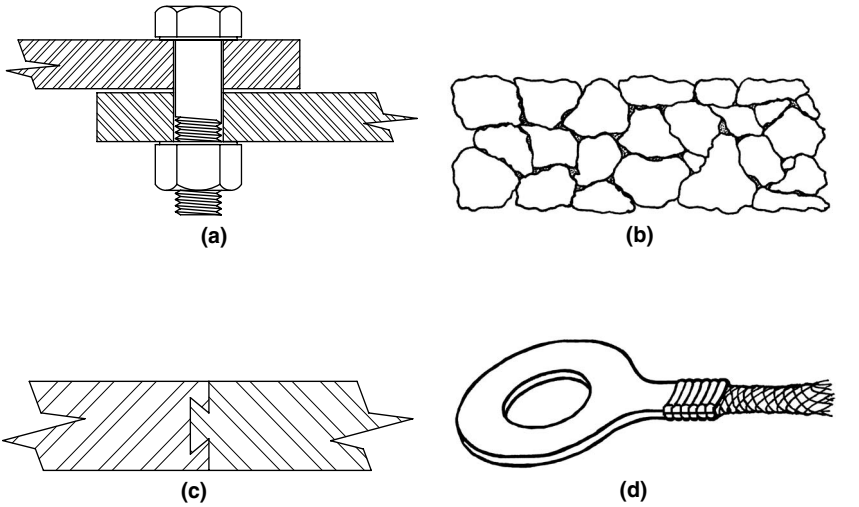

Figure 2.1 Schematic illustration of the use of supplemental devices known as ''fasteners'' in mechanical fastening (a) versus naturally occurring (b), designed-in (c), or formed-in (d) features in integral mechanical attachment; naturally occuring features are typefied by stones in a wall.

replacement of damaged parts, modification or reconfiguration of the assembly or structure, or the addition of accessories or new structure (i.e., expansion). This is a second major and unique advantage. A third advantage, also the direct result of no bonds being formed, is that most forms of mechanical fastening and some forms of integral attachment permit relative intentional motion between joined parts while still maintaining the needed geometric arrangement to achieve fit and function. An excellent example is a gear transmission box. If the gears in the assembly are held in the proper arrangement, proximity, and orientation but cannot at the same time be free to move in some intended direction (e.g., rotation), the transmission could not work. Allowing relative motion between the components of an assembly (at least for some direction of translation or rotation) in such an obvious way, but also in more subtle ways, while still providing needed mechanical alignment and structural integrity, is often vital for the assembly to be able to function. Limited motion to take up manufacturing tolerances (or ''slop''), or to damp out unwanted vibrations by friction at the joint, is also a critically important asset of mechanical joining.

A fourth and possibly most important advantage for many applications is that mechanical joining causes no change to the chemical composition or microstructure of the materials comprising the parts being joined. This is because the forces needed to hold the joint components together are purely mechanical. No atomic-level bonds are created, so no chemical interaction is necessary. The fifth advantage of mechanical joining is that it allows the joining of fundamentally different materials (e.g., metals to glass, metals to polymers, etc.). The sixth advantage is that it provides a simple means of achieving structural damage tolerance beyond inherent material damage tolerance. The joining of dissimilar materials is again made possible since bonding is neither

Table 2.1 Advantages and Disadvantages of Mechanical Joining (Including Fastening and Integral Attachment)

Advantages	*Disadvantages*
• Uniquely joins structures through interlocking and interference versus materials through bonding • Uniquely allows intentional disassembly without damaging parts involved • Uniquely facilitates maintenance, service, repair, upgrade, ultimate disposal, and portability • Uniquely allows intentional motion (for some degrees of freedom) in dynamic structures • Causes no changes to material microstructure or composition • Allows the joining of fundamentally different materials to one another • Provides a simple means of imparting structural integrity (beyond material) damage tolerance • Is simple and involves little or no special preparation of joints • Is relatively low in cost, requiring only limited operator skill versus other joining processes • Most forms of integral attachment are easy to automate (especially snap-fits) • Joint efficiency for most methods is high	• With a few exceptions (for some forms of integral attachment), accidental disassembly can occur without precautions • Stress concentrations are introduced by most methods at points of fastening or attachment • Some materials respond badly to induced stress concentrations • Joints typically allow fluid intrusion or leakage without special attention (e.g., gaskets, sealants) • Labor intensity for some mechanical fastening (e.g., rivets) can be high • Mechanical fasteners can add a weight penalty over other joining processes • Up-front costs (e.g., molds) for some integral attachments (e.g., snap-fits) can be high • Some methods of mechanical fastening (e.g., screw installation and bolting) can be difficult to automate

necessary nor involved. This means that other than for some possible electro-chemical or galvanic interactions that could lead to corrosion, for example, chemical compatibility is of little consequence. In mechnical joining, materials are not mixed; they are merely brought into contact. Structural damage tolerance is brought about by being able to limit the propagation of a growing crack (due to fatigue or corrosion, for example) to the structural element in which it initiated. There is no possibility of extension into an abutting, physically distinct element. Without actual elastic continuity of material, crack propagation is impossible.

A seventh advantage of mechanical fastening versus integral attachment using design features is that it is simple and requires little or no special preparation (e.g., for rivets, bolts, or machine screws, etc.). It requires only reasonable finishing to achieve

proper fit and only reasonable cleaning to avoid unwanted contamination.[3] For integral design features special preparation to create the features is obviously necessary, but usually with the added advantage over fasteners that assembly is made especially simple. In many cases this leads to an advantage of being able to automate assembly. Related to this seventh advantage are two other advantages: mechanical joining is usually relatively low in cost and normally requires only limited operator skill compared to other joining processes (e.g., especially welding, brazing, and soldering, and also, to a lesser degree, adhesive bonding). Finally, as mentioned above, mechanical joining (with only a few exceptions, such as bolting or keying) is generally amenable to simple automation.

Despite all of these advantages, nothing is perfect. There are some shortcomings and even genuine disadvantages to mechanical joining. First and foremost, in most of its forms (except some processed-in integral attachment), mechanical joining allows accidental disassembly unless special care is exercised. It is a simple truism, perhaps exacerbated by "Murphy's Law"[4]: What can be disassembled intentionally can disassemble accidentally. To prevent this, special care must be taken, at least during manufacture but preferably during design. For fastening, for example, lock-nuts or lock-washers can be employed to prevent accidental loosening and disassembly, nails can be driven at angles or "toed," and pins can be locked into place by wires or other pins (e.g., cotter pins). For snap-fit attachments, complex sequential motions can be used to cause assembly so that disassembly requires reversing these motions in the proper reverse sequence, or "safety locks" can be used to prevent accidental disassembly.

A second major disadvantage of all mechanical joining fastening and integral attachment is that stress concentrates at the point(s) of fastening or attachment. For fasteners requiring holes (e.g., bolts, rivets, screws, pins, and keys), the hole acts to create the stress concentration unless the fastener (e.g., rivet or pin) is "interference fit" or the fastener hole itself (e.g., for bolts or screws) is specially processed to create a compressive residual stress to offset tension stress buildup. For other types of fasteners (e.g., eyelets-and-grommets, staples, stitches) and for virtually all integral attachments, stress concentrates at the point of attachment or where the feature extends from the part to which it is integral. Such stress concentration is a particular concern in fatigue-critical structures but can also aggravate or accelerate corrosion.

A third disadvantage related to the above-mentioned stress concentration is that the utility of mechanical joining, with or without fasteners, is limited to certain materials. In inherently viscoelastic[5] polymers, stress concentration can lead to fastener-hole, fastener, or attachment feature distortion and loss of effectiveness. This is often called "cold flow" but also relates to "stress relaxation." In inherently brittle materials, such as ceramics or glasses, the concentration of stress can cause intolerable strain, leading to failure of the part, fastener, or attachment feature by fracture. Finally, the utility of

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[3] Unwanted contamination might involve debris that keeps joint faying surfaces from coming into proper contact or fit, or it might involve contamination that interferes with the proper functioning of friction-type joints (to be described later in this chapter).

[4] "Murphy's Law," a popular belief rather than actual law of nature, says, "Whatever can go wrong, will go wrong!"

[5] *Viscoelastic behavior* is time-dependent elastic strain following the onset and/or release of a load.

mechanical joining (especially fastening) can be limited by a material's anisotropy, particularly if that anisotropy leads to weakness through the fastening thickness, as in most laminated composites. The result can be fastener pull-through or pull-out.

A fourth disadvantage of mechanical joining can be the open nature of the joint between points of fastening, around fasteners, or between points of attachment. Such a joint allows moisture, water, air, or other fluid intrusion, permits leaks, and can accelerate corrosion in the oxygen-starved crevice, often aggravated by the dissimilar electrochemical nature of the joined materials or any residual stresses (e.g., from the ever-present stress concentration).

Other disadvantages of mechanical fastening are that the labor intensity for assembly can be high, especially for high-performance systems (e.g., preloaded bolts and upset rivets). There can also be a weight penalty when compared to integrally attached, welded, brazed, soldered, or adhesive-bonded joints, and joints can loosen in service as a result of vibration, mechanical flexing, thermal cycling, fastener relaxation, or joint (material) relaxation. Mold costs or other processing costs can be higher for some integral attachment methods, and these, too, can experience loosening or disassembly from flexing (especially during impact from dropping, for example) or material stress relaxation. However, assembly labor and cost for both labor intensity and required skill level are usually dramatically reduced with integral attachment.

As a final point, the efficiency of mechanical joints can vary considerably depending on the materials making up the joint elements, the design, size, number, and composition of fasteners or integral features, and the geometric factors involved in the joint design.

Table 2.2 compares the relative advantages and disadvantages of mechanical fasteners and integral attachments.

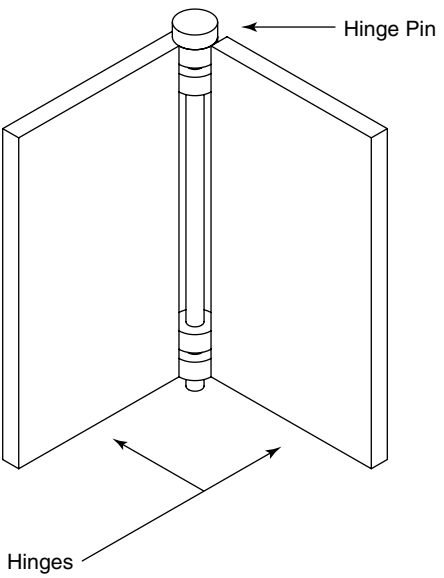
Figure 2.2 schematically illustrates some advantages of mechanical joining. Figures 2.3, 2.4, and 2.5 show examples of various applications of mechanical joining processes, including bolting, riveting, and snap-fit integral attachment.

2.3 SOURCES AND TYPES OF JOINT LOADING

As stated earlier, most joints are critical elements of assemblies and structures. They can be the weakest links in some assemblies or structures, thereby being the most likely areas of an assembly or structure to fail. Therefore, joints demand careful design for all forms of joining, including mechanical fastening or integral attachment. One of the most important aspects of the design of all joints is identifying the sources and estimating the magnitudes and directions of applied and/or internally generated loads. Such loads can be static (i.e., steady or unchanging) or dynamic (i.e., changing randomly or periodically), singly or in combination. The sources of loads can be weights or forces (e.g., from snow, water, wind, or other parts of the structure), forces from interacting structures, internal inertial forces, vibrations, transients (especially from startups, shutdowns, and faults), temperature changes or thermal excursions, fluid pressures, prime movers, and so on.

Table 2.2 Relative Advantages and Disadvantages of Mechanical Fastening and Integral Mechanical Attachment

Mechanical Fastening	*Integral Mechanical Attachment*
• Presently more common • Amenable to all materials, including composites • Adds to part count in design-for-assembly • Difficult to automate some types (e.g., bolting) • Assembly labor can be intensive but usually cheap • Adds relatively nothing to part cost • Accidental disassembly from loosening (usually from vibration) is possible • Fasteners can pose choking hazard to children (from loosening and fall out)	• Growing popularity • Amenable to polymers, metals, and ceramics (including cement/concrete) • Reduces part count in design-for-assembly • Facilitates automated assembly • Assembly labor is negligible • Part and (for polymers and ceramics) mold/form costs can be increased • Integral snap-fits preclude choking in children (e.g., in toys) • Accidental disassembly from flexing (especially from impact) can occur



(a) Relative Motion

Figure 2.2 Schematic illustration of some advantages of mechanical joining, including (a) ability to selectively allow relative motion between joined parts in some direction(s);

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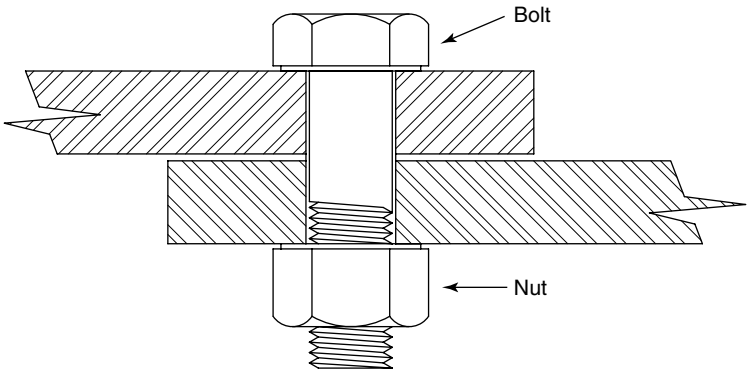
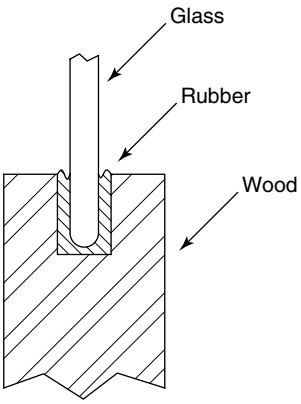
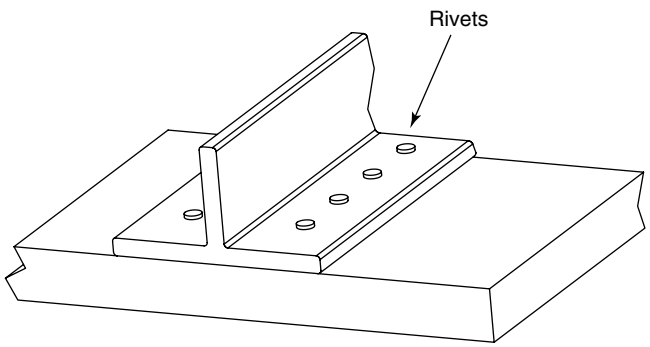


(b) Intentional Disassembly



(c) Dissimilar Materials



(d) Damage Tolerance

Figure 2.2 *cont'd* (b) ability to allow intentional disassembly without damaging parts; (c) ability to join fundamentally dissimilar materials; and (d) ability to impart tolerance to damage in the structure beyond that inherent in the materials comprising the structure.

Figure 2.3 High strength bolting is widely used in the assembly of flanged pumps, valves, pipes, and fittings in a petroleum refinery to allow easy assembly of pre-fabricated components from multiple sources, as well as easy replacement. (Courtesy of Marathon Ashland Petroleum LLC, Findlay, OH, with permission.)

Figure 2.4 Riveting is widely used in the assembly of conventional Al-alloy aircraft airframe components and subassemblies, such as this wing for a T38 training aircraft. (Courtesy of Northrop Grumman Corporation, El Segundo, CA, with permission.)

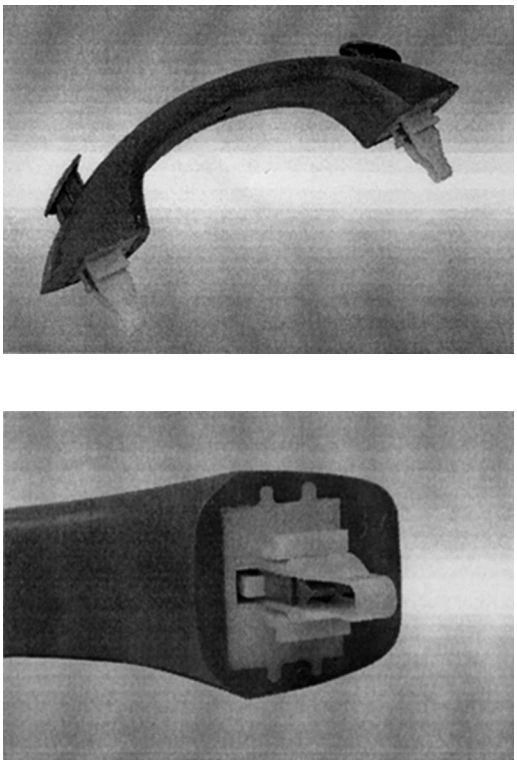


Figure 2.5 Integral snap-fits are now commonly used in the assembly of automobile trim, for example, such as this assist handle shown overall (a) and in close-up of the snap (b). (Courtesy TRW Engineered Fasteners & Components, Westminster, MA, with permission.)

Regardless of the source of loads, mechanically fastened or integrally attached joints are of two principal types, based on the direction of primary loading versus the fastener's or attachment feature's axis: (1) *shear-loaded joints*, in which the primary loads are applied at right angles to the axes of the fasteners or attachment features; or (2) *tension-loaded joints*, in which the primary loads are applied more or less parallel to the axes of the fasteners or attachment features (see Figure 2.6). The design procedures for shear-loaded and tension-loaded joints are quite different.

2.4 SHEAR-LOADED FASTENED JOINTS

2.4.1 Types of Fastened Shear-Loaded Joints

Two basic joint configurations can be loaded predominantly in shear: single-lap or single-overlap joints and double-lap or spliced-butt joints. Figure 2.7 shows how threaded fasteners can be used to resist two different types of loading, shear or tension. When used to resist shear loading, two different subtypes are defined as *bearing-type*

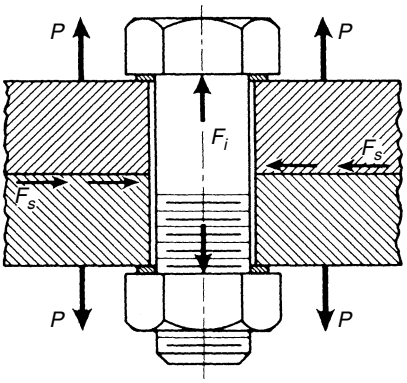


Figure 2.6 Schematic illustration showing how bolted as well as some other fastened joints can operate to resist shear loading, tension loading, or combined shear and tension loading, depending on the type of fastener used.

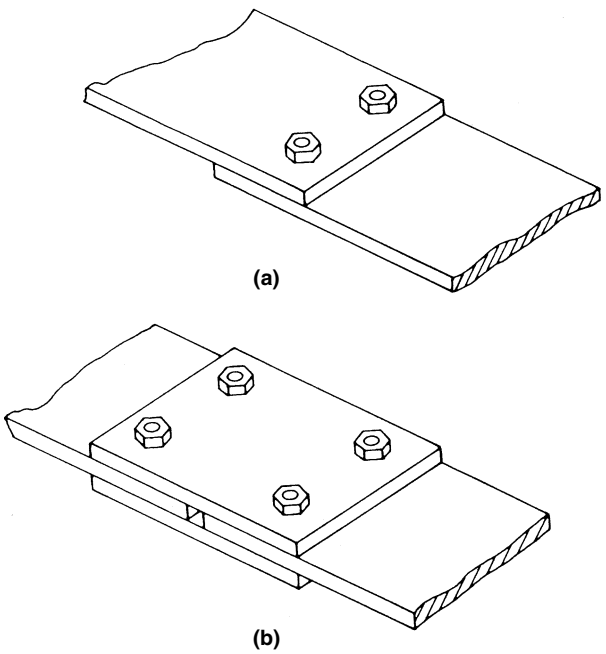


Figure 2.7 Schematic illustration of shear-loaded (a) single-lap (or single-overlap) and (b) double-lap (or spliced-butt) fastened joints. (Reprinted *from Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.1, page 29, with permission of Elsevier Science, Burlington, MA.)

shear-loaded joints and *friction-type* shear-loaded joints. In bearing-type shear-loaded joints, the fasteners (regardless of their specific types) act as pinning points to prevent movement of one joint element relative to the other, at least in translation (versus

rotation). The joint elements are held together by shear in the fastener and the bearing force or stress in the joint elements created by the fastener. Common examples of fasteners properly used for bearing-type shear-loaded joints are nails, rivets, pins, and keys (see Chapter 3). In friction-type shear-loaded joints, the fasteners must create a significant amount of clamping force on the joint, holding the joint elements together and preventing any motion or slip. The resulting friction created between the joint elements is a result of their coefficient of friction and applied normal (clamping) force. When these joints are operating properly, the frictional force developed precludes the fastener from having to carry and/or apply a bearing force by not allowing slip of the joint elements. Only bolts can be properly used for such joints, although certain rivets are used on occasion.

Figure 2.8 schematically illustrates bearing- and friction-type shear-loaded joints, including the loading. Only bolts or machine screws (see Chapter 3) can properly and reliably be used in friction-type joints because only these two fastener types can be counted on to develop the level of clamping force needed to produce the necessary friction

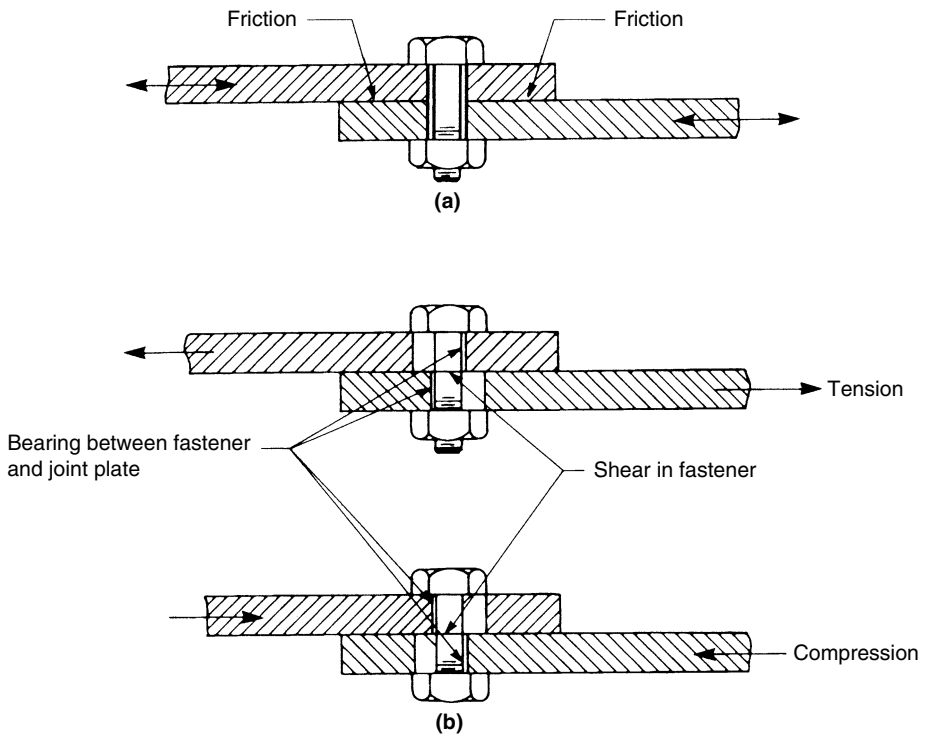


Figure 2.8 Schematic Illustration of (a) friction-type versus (b) bearing-type shear-loaded fastened joints. The difference in how the joint elements resist bearing stress under applied tension and compression forces is shown in (b). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.2, page 30, with permission of Elsevier Science, Burlington, MA.)

force to resist slip.[6] Rivets, while occasionally used in such joints, are a risk because when they are upset (or "set hot") to develop a clamping force through thermal contraction in their shanks, such clamping force can easily be lost, presuming it was even developed initially. Friction-type connections are generally used to resist fatigue and/or damp vibrations, with good examples being in bolted truss-type bridges and in large built-up columns and overhead beams used to support the ceilings in subway systems.

The shear stress in bearing-type connections, or the friction in friction-type connections, is related to the arrangement of the pieces or structural elements comprising the joint, as shown in Figure 2.9. This figure shows single- and double-lap shear. The advantages of single-laps are ease of assembly and cost, and the advantages of double-laps are elimination of eccentric loading (see Subsection 2.4.5) and reduction of shear stresses at each of the multiple shear planes in the fastener in bearing-type joints.

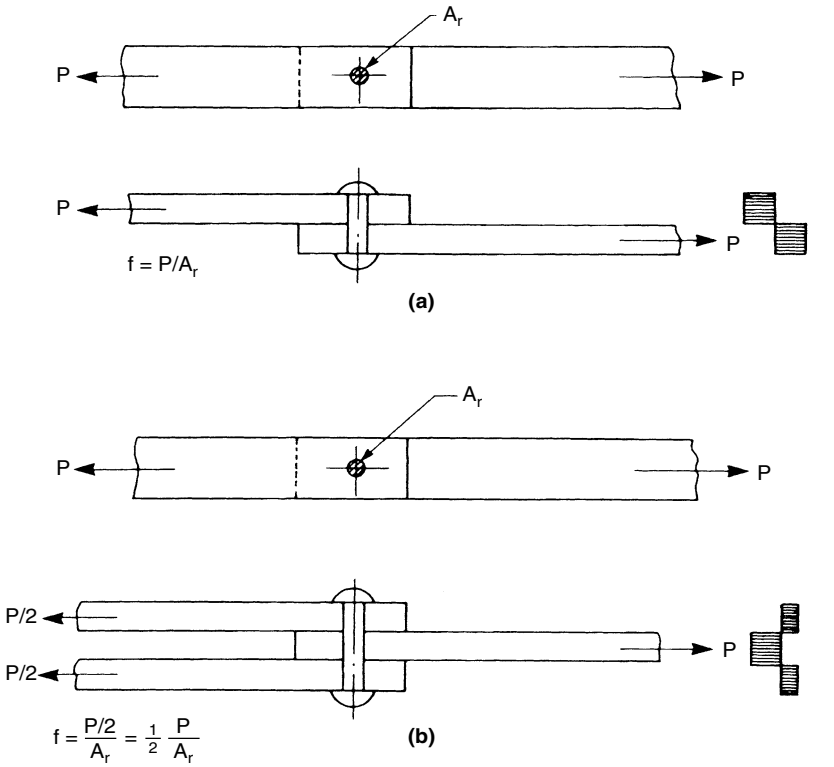


Figure 2.9 Schematic illustration of (a) single-shear versus (b) double-shear arrangements of joint elements in bearing-type shear-loaded fastened joints. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.3, page 31, with permission of Elsevier Science, Burlington, MA.)

[6] Actually, so-called "machine screws" (which will be described in Chapter 3) are, for all intents and purposes, just small bolts. Like bolts, machine screws can also be used with or without nuts and can also be used in friction-type joints. However, required friction loads must be lower because achievable clamping forces or preloads for these small fasteners are more limited.

2.4.2 Fastener Spacing and Edge Distances

Because mechanical fasteners impose a stress on and develop a stress concentration in the joint elements at each fastener under the application of loads, they must be carefully located relative to one another (i.e., their spacing) to help distribute loading, and relative to the edge of the joint elements (i.e., their edge distance) to prevent tear-out. This is true for both shear-loaded types of joints and fasteners, as are being described here, and for tension-loaded types of joints and fasteners to be described in the next subsection. Tear-out is especially a concern with bearing-type shear-loaded joints and fasteners. Bearing forces imposed by these types of fasteners on the joint elements under loading can first cause elongation of the fastener holes due to yielding and plastic deformation of the material surrounding the holes on opposite sides of opposing structural elements. The bearing forces could also possibly tear out slugs of material from the joint element or from the holes to the element's edge if edge distances are insufficient. While this can occur under static loading, the situation can be even worse for dynamic loading by impact or by fatigue.

Recommended spacings between fasteners and distances for locating fasteners from edges are given in various specifications. Values differ slightly from specification to specification based on application in terms of acceptable (or allowable) loading or stress levels, consequence of failure (i.e., criticality of the structure), and safety (especially for the public). Relevant examples are Specifications J3.8 and J3.9 developed by the American Institute of Steel Construction (AISC). As shown schematically in Figure 2.10, these specifications typically require spacing between fasteners of $\geq 2\frac{2}{3}$ times the diameter of the fastener (d), with 3 times preferred, and edge distances $\geq 1\frac{3}{4}$ times the diameter of the fastener for sheared edges or $1\frac{1}{4}$ times the diameter of the fastener for rolled edges.[7] In

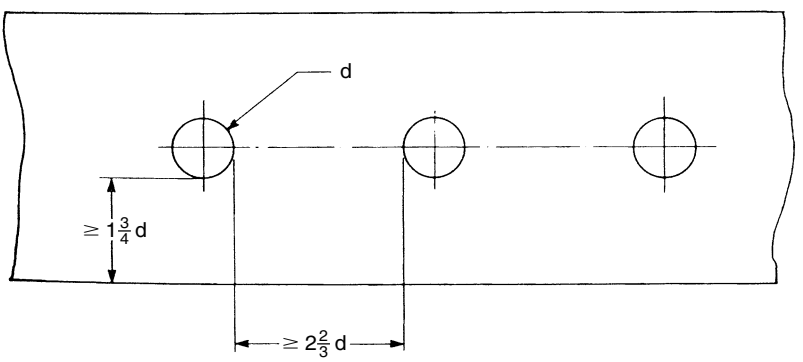


Figure 2.10 Schematic illustration of AISC-specified spacing and edge distances for fasteners used in steel construction. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.4, page 31, with permission of Elsevier Science, Burlington, MA.)

[7] The difference between rolled and sheared edges is due to the roughness of the edge produced and the introduction of some slight compressive residual stress by rolling.

other specifications edge distances and fastener spacings can vary from these AISC specifications, but careful consideration should always be given to these parameters. Edge distance becomes a particular concern in certain viscoelastic materials like polymers and polymer-matrix composites, or in any thin joint elements where bearing loads cannot be well tolerated. Fastener spacing becomes a particular concern in structures and joints required to be leaktight under positive internal pressure, as joint opening can occur between points of fastening or attachment.

2.4.3 Effect of Fastener Holes on Joint Net Area

The net area, A_n, of a structural member in a joint is the product of the member's width (taken to be the dimension parallel to the fastening line) and its thickness, less the sum of the area lost due to all the fastener holes. (Each fastener hole is assumed to be the diameter of the fastener hole plus some safety factor, typically $\frac{1}{16}$ in., for dimensions in English units.) Figure 2.11 (a and b) schematically illustrates two patterns of fastener holes. The first consists of a single row along the structural member's length (or one hole across the member's width), and the second consists of a double row along the structural member's length (or two holes across the member's width). The net areas for these two and all situations are given by:

$$A_n = t\,[w - n(d + \frac{1}{16}\text{ in.})] \tag{2.1}$$

where t is the joint element thickness (in inches), w is the joint element width (in inches), n is the number of fastener holes along the straight path across the width of the joint element, and d is the diameter of the fastener hole (in inches). The additional factor of $\frac{1}{16}$ in. is to account for hole tolerance errors. (An identical equation, but with a different tolerance error factor—typically 1.5 mm—is employed for fastening using SI metric dimensions.)

For a pattern of holes that extends across a joint element in a diagonal or zig-zag line (as in Figure 2.11c), the net width of the element is obtained by subtracting the sum of the diameters of all holes on a transverse line across the section, and adding (for each so-called "gage space" or line segment (m) in the pattern) the quantity:

$$s^2/4g \tag{2.2}$$

where s is the longitudinal center-to-center spacing or "pitch" of any two consecutive fastener holes (in inches) and g is the transverse center-to-center spacing or "gauge" between fastener gauge lines or rows (in inches). This gives the general equation:

$$A_n = t[w - n(d + \frac{1}{16}\text{ in.}) + m(s^2/4t)] \tag{2.3}$$

where t and s are as above, w is the width of the structure element (in inches), n is the number of fastener holes along the chosen path or load line, d is the diameter of the fastener hole (in inches), and m is the number of angled line segments. (A similar equation applies for metric fastening, but with a 1.5-mm hole-tolerance factor.)

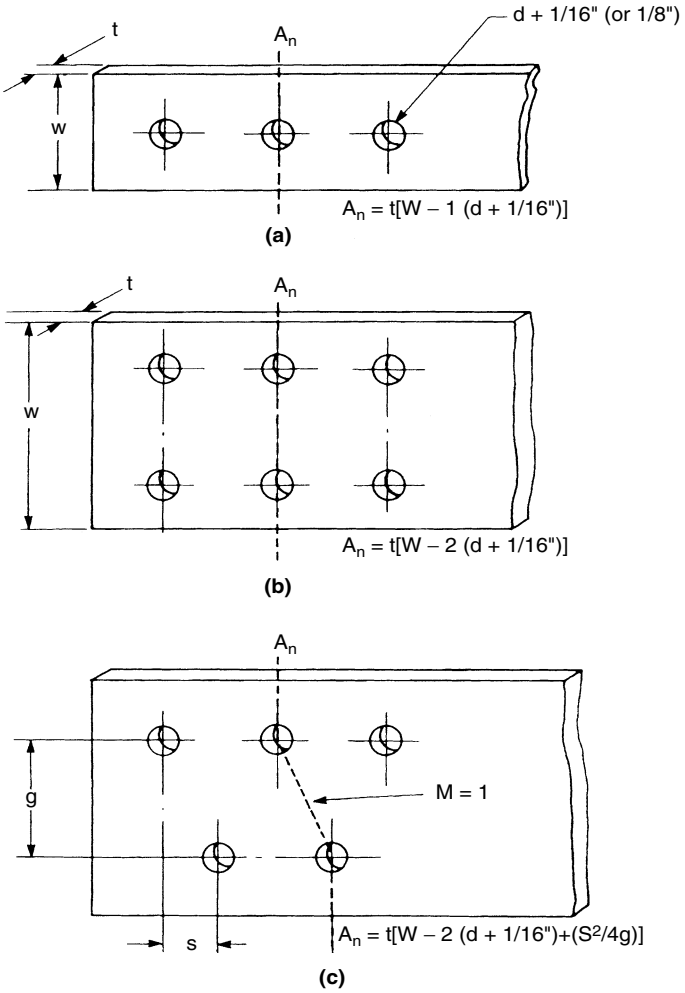


Figure 2.11 Schematic illustration showing the effect of various patterns of fastener holes on the net load-bearing area of a fastened joint: (a) single row and double row with (b) a chain pattern and (c) a staggered pattern of holes. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.5, page 33, with permission of Elsevier Science, Burlington, MA.)

Illustrative Example 2.1—Determining Net Area for a Joint.

For a $\frac{3}{4}$-in. thick joint element containing a staggered pattern of nominal $\frac{3}{8}$-in. diameter bolt holes in three rows, as shown in Figure IE 2.1, there is the gross area (where there are no fastener holes across the width of the joint element) and two different net areas—one along the straight transverse path AC and the other along the zig-zag path ABC. The various areas are calculated by:

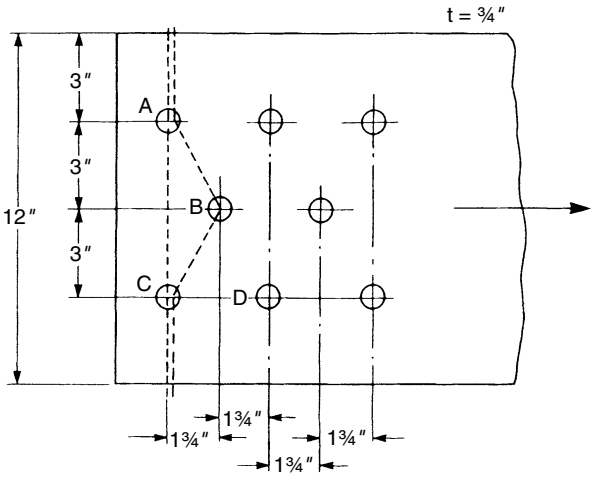


Figure IE 2.1 Schematic illustration showing possible load paths or joint failure paths as these affect net joint area: A-C, straight across and A-B-C or A-B-D as alternative zig-zig paths. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.6, page 34, with permission of Elsevier Science, Burlington, MA.)

$$A_{gross} = \frac{3}{4}\,\text{in.}(12\,\text{in.}) = 9.0\,\text{in.}^2$$

while

$$A_{net\ AC} = \frac{3}{4}\,\text{in.}[12\,\text{in.} - 2(\frac{3}{8}\,\text{in.} + \frac{1}{16}\,\text{in.})] = 8.34\,\text{in.}^2$$

and

$$\text{A}_{\text{net ABC}} = \frac{3}{4}\,\text{in.}[12\,\text{in.} - 3(\frac{3}{8}\,\text{in.} + \frac{1}{16}\,\text{in.}) + 2(1\frac{3}{4}\,\text{in.})^2/4(3\,\text{in.})] = 8.73\,\text{in.}^2$$

Clearly, the smaller area (along the path AB) governs the design, as this area gives rise to the highest stress from a given applied load.

2.4.4 Allowable-Stress Design Procedure

The predominant procedure for designing shear-loaded fastened joints is the *allowable-stress design procedure*. In this procedure, all fasteners are assumed to carry an equal share of the applied loads. In fact, this assumption is only truly valid for joints that are composed of perfectly rigid materials (which is not the real case and is least valid for joints containing multiple rows of fasteners). Nevertheless, the assumption is generally accepted and is perfectly safe when conservative allowables are used (which is one reason conservative allowables or factors of safety are used, as when used, as the result of imprecise analysis). In fact, a joint can reasonably be assumed to be rigid when (1) plane

sections in the structural member (e.g., a gusset plate) remain plane and do not warp and (2) a straight line from the center of gravity (or centroid) of the fastener pattern remains straight after a torque is applied. The assumption of equally shared loading also depends on all fasteners being of the same size and material, all fitting with equal tightness in their fastener holes, and all being equally tightened (at least for threaded fasteners such as bolts). These last two assumptions are often not valid.

Empirical means have been used to determine the maximum working stresses that can be allowed in the fasteners and joint members under the assumption of equally shared loading. Various professional society specifications (or, in some cases, codes) use slightly different allowables. However, two common specifications are those of the American Society for Testing Materials (ASTM) and the American Institute for Steel Construction (AISC). The AISC specification specifies the allowable stress as follows:

"The allowable stress σ_t shall not exceed 0.60 σ_y [yield stress] on the gross area nor 0.50 σ_u [ultimate stress] on the effective area."

Under the allowable-stress design procedure for bearing-type shear-loaded joints, the various elements of the joint (including structural members and fasteners) must be sized so that the following conditions are satisfied: (1) the fasteners will not fail in shear by overload; (2) the joint plates will not fail in tension by overload; (3) the fastener holes will not be deformed by bearing loads from the fasteners; and (4) the fasteners will not tear out of the joint plates at edges. These various modes of potential failure are shown schematically in Figure 2.12. None of these modes will occur if the appropriate allowable stresses are not exceeded in the fasteners (i.e., shear allowables) or in the joint plates (i.e., tension overload or bearing allowables) as given in design tables such as those in the *Standard Handbook of Machine Design* (Shigley and Mischke, 1986). Some allowable stresses compiled from this and other similar sources are given in Table 2.3.

The great advantage of the allowable-stress design procedure is not that it precludes failure under any conditions (although it does so under normal operating conditions!), but that it allows the designer to choose the mode by which the structure would ultimately fail. Thus, should the structure fail, this procedure allows the designer to choose the "weakest link" in the structure, minimizing serious—especially catastrophic—or costly consequences.

The allowable-stress design procedure is probably best understood through an example, as follows.

Illustrative Example 2.2—Allowable-Stress Design Procedure Applied to Bearing-Type Shear-Loaded Joints.

The double-lap shear joint shown schematically in Figure IE 2.2 is composed of ASTM A36 steel, contains five 22-mm (nominally, $\frac{3}{4}$-in.) diameter ASTM A325 steel bolts arranged as shown (although the specific pattern does not matter for symmetrical loading); the bolts have a thread pitch of 2 mm per thread (or, in the Unified system given in Chapter 3, there are 12 threads per inch). One of the shear plates in the double-lap joint passes through the unthreaded portion and one passes through the threaded portion of each bolt. The problem is to determine the various stresses produced in the fastener and in the joint plates by a load of 300 kN (67,000 lbs. force).

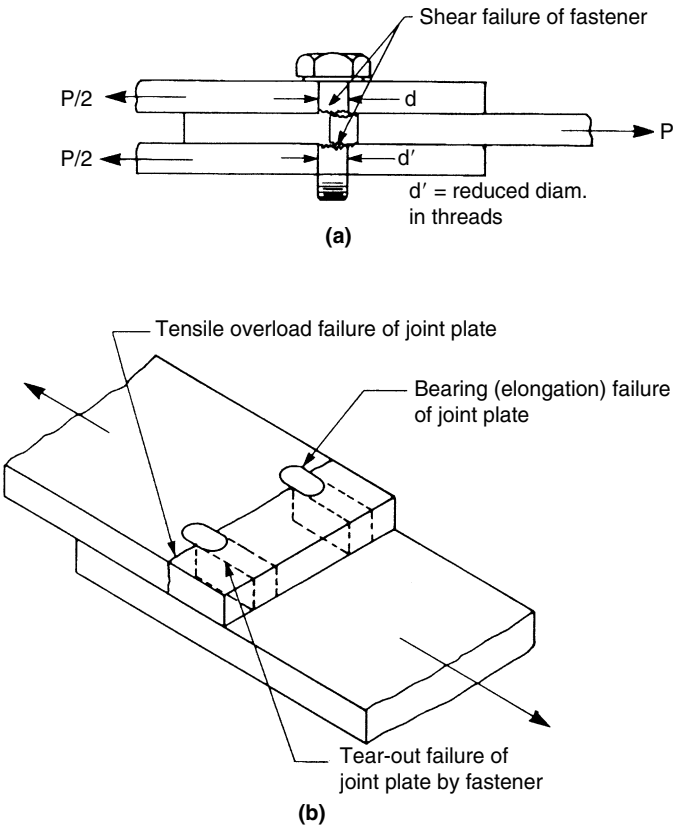


Figure 2.12 Schematic illustration of the various modes of potential failure in a shear-loaded fastened joint operating in bearing. Shear in the fastener is shown in (a), while tensile overload of the joint element through the section with the smallest net cross section, bearing-induced hole elongation, and tear-out of the joint element for fastener holes placed too close to the edge is shown in (b). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, 1993, Fig. 2.7, page 35, with permission of Elsevier Science.)

1. Determining the shear stress in the fasteners.

The shear stress produced in a fastener by a given load depends on the actual cross-sectional area of the fastener, and this is affected by whether the fastener is threaded or unthreaded in the region (or at the plane) through which a shear plane in the joint elements passes. For an unthreaded rivet, for example, the shear stress τ within each fastener is:

$$\tau_{unthreaded} = F/bmA_{unthreaded} \tag{2.4}$$

where F is the force in kilonewtons (or lbs. force), b is the number of shear planes that actually pass through the unthreaded fastener or portion of the shank of a fastener,

Table 2.3 Allowable Stresses for Some Important Fastener and Joint Plate Materials*

	Allowable Stress, in MPa (kpsi)		
Material/Condition	*Tension*	*Shear*	*Bearing*
Joint plate materials:			
ASTM A36	152 (22.0)	100 (14.5)	335 (48.6)
ASTM A440 (2.48 safety factor) (25.4–28.2)	175–194	—	—
ASTM A514 (2.00 safety factor)	345–448 (50.0–65.0)	—	—
ASTM A515 (stress in net section)	95 (14.0)	—	—
58-ksi ultimate tensile steel			
25 in. joint with A325 bolts	—	160 (23.2)	—
80 in. joint with A325 bolts	—	200 (29.0)	—
100-ksi ultimate tensile steel			
20 in. joint with A490 bolts	—	54 (50.0)	—
90 in. joint with A490 bolts	—	276 (40.0)	—
Rivet materials:			
ASTM SA31 (used in A515 plate)	—	62 (9.0)	124 (18.0)
ASTM SA502-1 (used in A36 plate)	—	93 (13.0)	276 (40.1)
Bolt materials:			
ASTM A325			
Bearing-type joints			
-threads in shear plane	—	145 (21.0)	—
-no threads in shear plane	—	207 (30.0)	—
Friction-type joints			
-clean mill scale	—	52 (17.5)	—
-blasted clean	—	190 (27.5)	—
-blasted + Zn paint	—	203 (29.5)	—
ASTM A490			
Bearing-type joints			
-threads in shear plane	—	193 (28.0)	—
-no threads in shear plane	—	276 (40.0)	—
Friction-type joints			
-clean mill scale	—	152 (22.0)	—
-blasted clean	—	238 (34.5)	—
-blasted + Zn paint	—	255 (37.0)	—

*Table compiled from data found in several references, especially J. Shigley and C. Mischke, *Standard Handbook of Machine Design.* New York, McGraw-Hill, 1977, with permission.

m is the number of fasteners in the joint, and $A_{unthreaded}$ is the cross-sectional area of the body of the unthreaded fastener (here, a rivet) or unthreaded region of a threaded fastener (like a bolt) in square millimeters or square inches.

For a threaded fastener such as a bolt, the shear stress τ within each fastener is:

$$\tau_{thread} = F/bmA_{thread} \tag{2.5}$$

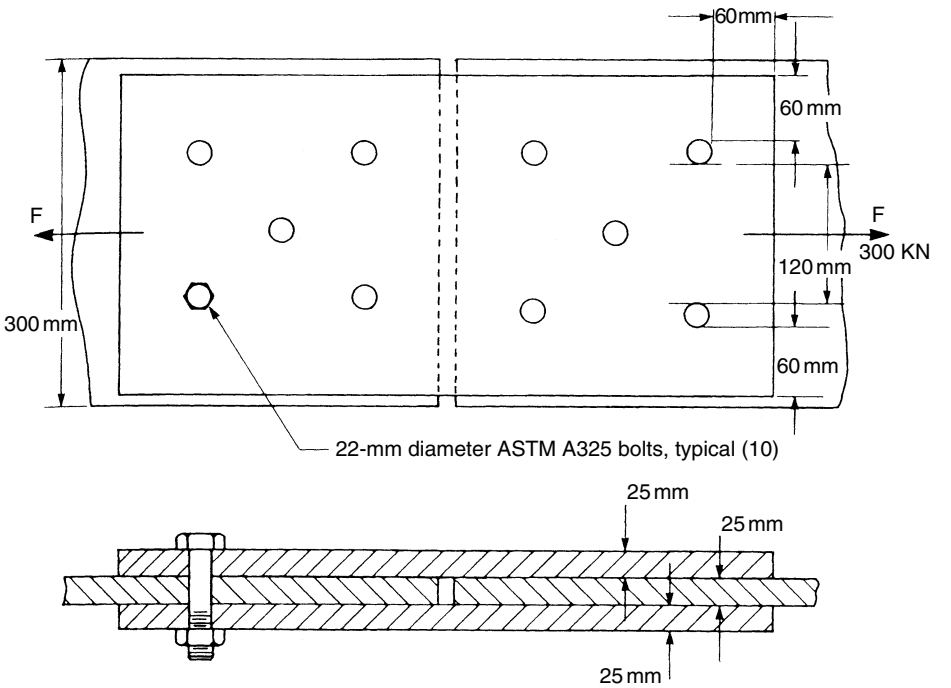


Figure IE 2.2 Schematic illustration showing a fully dimensioned double-lap shear-loaded fastened joint operating in bearing. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.8, page 37, with permission of Elsevier Science, Burlington, MA.)

where F, b, and m are as above, and $A_{threaded}$ is the cross-sectional area of the fastener in the region of the thread in square millimeters or square inches.

A bolt can have different cross-sectional areas depending where a shear plane involved in a particular joint passes through it (see Figure 2.13). If a shear plane passes through the unthreaded portion of the body of the bolt (or through an unthreaded rivet or pin), the area of the bolt (or rivet or pin) is:

$$A_{unthreaded} = \pi d^2/4 \tag{2.6}$$

where d is the diameter of the unthreaded body.

If a shear plane passes through the threaded portion of a bolt, the cross-sectional area is obviously reduced by the threads (specifically, the thread troughs). For threads under the Unified system (see Chapter 3), the area of the bolt is given by:

$$A_{thread} = \pi[d - (0.9743/n)]^2/4 \tag{2.7}$$

while for metric threads, the area is given by:

$$A_{thread} = \pi[d - (0.9382P)]^2/4 \tag{2.8}$$

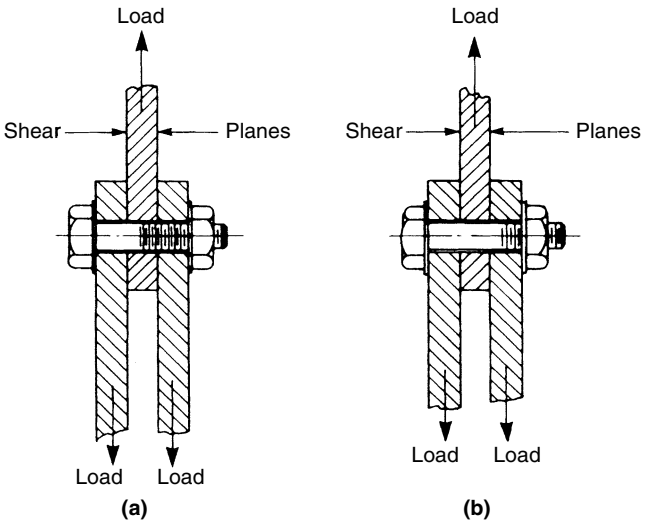


Figure 2.13 Schematic illustration showing locations of multiple shear planes passing through a fastener, including: (a) two shear planes, one of which passes through the threaded and one through the unthreaded portion of a bolt, and (b) two shear planes passing through the unthreaded portion of a bolt. Figure 2.9 shows a fastener with a single shear plane passing through it. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.9, page 37, with permission of Elsevier Science, Burlington, MA.)

where d is the bolt's nominal diameter (in millimeters or inches), n is the number of threads per inch (for the Unified system), and P is the pitch of the threads in millimeters (for the metric system).

The total cross-sectional area through the bodies of all five bolts in this illustrative example is thus:

$$5A_{unthreaded} = 5(\pi)(22\,\text{mm})^2/4 = 1,900\,\text{mm}^2(2.94\,\text{in.}^2) \qquad \text{(using Equation 2.5)}$$

and through the threads is:

$$5A_{thread} = 5(\pi)[22\,\text{mm} - (0.9382)(2\,\text{mm})]^2/4 = 1,572.5\,\text{mm}^2(2.43\,\text{in.}^2)$$

Using Equation 2.5, the shear stress in each bolt in the area of the threads (i.e., where the area is the smallest) is:

$$\tau = 300\,\text{kN}/(2)(1,\ 572.5\,\text{mm}^2) = 95.4\,\text{MPa}(13.8\,\text{ksi})$$

The value of b is taken to be 2 here, to be conservative by assuming that both shear planes pass through the threads of the bolts.[8]

[8] The other, more accurate approach is to calculate τ assuming that one shear plane passes through the unthreaded region and one through the threaded region of all five bolts, to give: $\tau = 300\,\text{kN}/1,900\,\text{mm}^2 + 1,572.5\,\text{mm}^2 = 86.4\,\text{MPa}(12.5\,\text{ksi})$, where $1,900\,\text{mm}^2$ and $1,572.5\,\text{mm}^2$ are the two areas above.

The value of shear stress calculated is well within the shear stress of 145 MPa (21.0 ksi) allowed for A325 steel bolts, and is therefore acceptable.

2. Determining the tensile stress in the joint plates within the joint itself.

The tensile stress σ in the joint plates at the joint is taken to be the applied load divided by the net cross-sectional area of the joint plate at the point where the greatest number of fastener holes are located along the load line (see Illustrative Example 2.1). For this example, calculating the cross-sectional area of the row containing the most bolts (i.e., the lowest cross-section of A36 steel) by adding a factor of approximately 1.5 mm (or $\frac{1}{16}$ in.) extra for each fastener hole's diameter along either line AC or line ABC and using Equations 2.1 and 2.3 gives:

$$A_{AC} = 25\,\text{mm}[300\,\text{mm} - 2(22\,\text{mm} + 1.5\,\text{mm})] = 6,325\,\text{mm}^2$$

while

$$\begin{aligned} A_{ABC} &= 25\,\text{mm}[300\,\text{mm} - 3(22 + 1.5\,\text{mm}) + 2(60\,\text{mm}^2)/4(25\,\text{mm})] \\ &= 25\,\text{mm}[300\,\text{mm} - 70.5\,\text{mm} + 72\,\text{mm}] = 7,537.5\,\text{mm}^2 \end{aligned}$$

So, the path (or load line) with the smallest area is AB, with an area of $6,325\,\text{mm}^2$.

Thus, the stress in two such sections (given that there are two splice plates making up the joint) is:

$$\sigma = F/A = 300\,\text{kN}/(6,325\,\text{mm}^2)(2) = 23.7\,\text{MPa}(3.4\,\text{ksi})$$

This is well within the allowable tensile stress value of 152 MPa (22.0 ksi) for A36 steel joint material. Therefore, the joint is acceptable in terms of joint plate overload.

3. Determining the bearing stress on the joint plate.

If the fasteners exert too great a stress on the plates making up the joint, the joint can fail if the bolt holes elongate.[9] From Figure 2.14, the bearing stress σ_B on the joint plate is given by the pressure of the bolt on the projected area onto the joint plate. So:

$$\sigma_B = F/md\ell \tag{2.9}$$

where F is the applied load, m is the number of fasteners causing bearing (along *all* load lines) or the number of fasteners in the pattern (on one side of a joint), d is the fastener's diameter, and ℓ is the fastener's total length being acted upon by joint plates (in bearing) or the joint plate "stack height" or "stack thickness."

Thus:

$$\sigma_B = 300\,\text{kN}/(5)(22\,\text{mm})(3 \times 25\,\text{mm}) = 36.4\,\text{MPa}(5.3\,\text{ksi})$$

[9] Failure might be considered to have occurred as soon as the holes elongate enough to cause the joint to be loose or move. On the other hand, failure may not be considered to have occurred until these elongated holes fail in fatigue, as they almost certainly will.

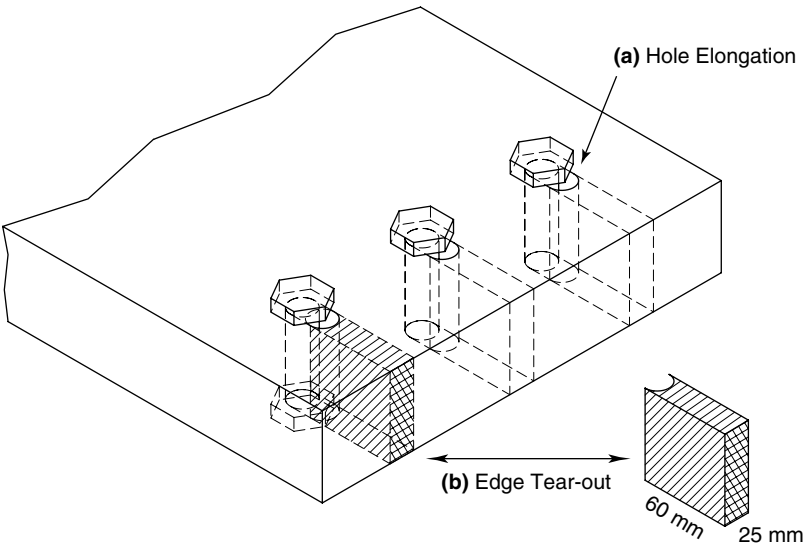


Figure 2.14 Schematic illustration showing the effect of the bearing stress imposed by a fastener on a joint element in a shear-loaded joint, including hole elongation and fastener-edge tear-out, which can only occur for fasteners arranged in a single row too close and parallel to an edge. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.10, page 39, with permission of Elsevier Science, Burlington, MA.)

This falls well within the allowable bearing stress of 335 MPa (48.6 ksi) for A36 steel plates and is therefore acceptable.

4. Determining the fastener tear-out stress.

Finally, the designer must ensure that fasteners will not tear out of the joint plate as shown in Figure 2.14. This can only occur if the fasteners are located so close to the edge of the plate that the shear stress developed by bearing exceeds the ability of the plate material to sustain that stress over all shear planes from the fasteners (i.e., fastener hole centerline) to the edge. In fact, tear-out cannot occur if there are multiple rows of fasteners, given the assumption of equal sharing of load by all fasteners. This is because a slug of material near the edge could not tear out if the strain due to elongation at the fastener holes caused by bearing did not exceed the strain needed to cause shear overload over all the aforementioned planes.

In this illustrative example there are multiple rows of fasteners, so tear-out could not occur. To do so, holes on the second and third rows from the edge would have to elongate in bearing by enough to cause tear-out of slugs between the first row and the edge. If there were three bolts in a row, however, there would be six shear planes (or areas) to cause tear-out. Hence, the tear-out stress would be:

$$\tau = F/mth \tag{2.10}$$

where t is the thickness of the plate, h is the distance from the center of the fastener hole to the edge, m is now the number of tear-out shear planes, and F is the applied load.

Thus:

$$\tau = 300\,\text{kN}/6(22\,\text{mm})(60\,\text{mm}) = 37.8\,\text{MPa}(5.5\,\text{ksi})$$

Since this value is well within the allowable shear strength of 100 MPa (14.5 ksi) for A36 steel plates, it would be acceptable for this single-row-of-three arrangement.

The joint in Figure IE 2.2 therefore meets all of the design requirements for the given load. It is not at risk but would fail first by fastener shear, as this stress is closer to the allowable than all the others. It would thus reach failure sooner than all the others if the applied load increased.

For bearing-type joints, the design is limited by whichever of the four stresses calculated by the allowable-stress design procedure exceeds the appropriate allowable stress. The procedure can be used in either of two ways: (1) to check that all four stresses are below the allowable stresses, or (2) (a) to determine the limiting load of a design using the allowable stresses and (b) to calculate the lowest load to cause failure by one of the four modes.

For friction-type joints, the design analysis is slightly different than for bearing-type joints. Recall that in a friction-type joint the intent is to have an appropriate fastener (i.e., a bolt or machine screw or, some might say, a "hotset" rivet) apply a clamping load high enough to cause sufficient frictional force to resist the applied load, thereby protecting the fastener from ever having to carry shear or cause bearing. The necessary slip resistance, as the frictional force developed in this way is called, depends greatly on the surface conditions of the structural joint element materials at their joint faying interface(s). Typical slip coefficients of friction, μ_s, can be found in tables in various handbooks. Table 2.4 compiles typical slip coefficients from a number of such handbooks. Values can be seen to be highly dependent on the treatment and condition of the joint surfaces, which must be carefully stipulated and controlled for such friction-type joints to work reliably. For example, surfaces cannot be painted unless painting is called for and an approved paint is used. No lubricants can ever be used if not planned for at the design stage. One even needs to be concerned about water infiltration in such joints, since water acts as a lubricant and drastically lowers the slip coefficient of a joint designed to be dry during operational service.

According to the *Standard Handbook of Machine Design* (Shigley and Mischke, 1986), "The ultimate strength of a friction-type joint is considered to be the lower of its slip resistance or its bearing strength." The bearing strength is computed by using the same equations as in IE 2.2, except that one would enter the allowable stress for each material used in the joint plates and fasteners and compute the force that would be required to produce a stress to cause shear overload in the fasteners, tensile overload in joint plates, elongation (in bearing overload) of fastener holes in the joint plates, or fastener tear-out from the joint plate near its edge. The lowest of these forces is then compared to the force necessary to cause slip (or the slip resistance) calculated earlier for an assumed value of average fastener joint preload. The lower of these determines the ultimate load-carrying capacity of the friction-type joint. This procedure is shown in the following example.

Table 2.4 Typical Slip Coefficients for Joint Elements in Friction-Type Shear-Loaded Joints (Prepared by Various Methods)*

Typical Slip Surfaces	*Coefficient,* μ_s
For steel prepared by various means:	
Free of paint, applied finishes, oil, dirt, loose rust or scale, etc.	0.45–0.7
Clean mill scale	0.35–0.45
Greasy	0.1–0.25
Hot dipped galvanize	0.16
Hot dipped galvanize, wire brushed	0.3–0.4
Grit blasted	0.3–0.55
Sandblasted	0.45–0.55
Metallized Zn sprayed onto grit-blasted surface	0.4–0.45
Metallized Al sprayed surface	0.55–0.65
For other materials (dry):	
Al on Al (pure or alloys)	0.8–1.05
Brass on steel	0.50–0.55
Cast iron on cast iron	1.0–1.1
Cu on steel	0.5–0.6
Cu on glass	0.65–0.70
Glass on glass	0.9
Glass on glass (greasy)	0.01–0.05
Ni on Ni (pure or alloys)	0.9–1.10
Oak on oak (parallel to grain)	0.6–0.65
Oak on oak (perpendicular to grain)	0.5–0.55
Plastic on steel	0.3–0.4
Teflon on Teflon	0.04
Tungsten carbide on tungsten carbide	0.2
Tungsten carbide on steel	0.4–0.5

*Data are compiled from numerous general references and are intended as guidelines only!

Illustrative Example 2.3—Allowable-Stress Design Procedure Applied to a Friction-Type Shear-Loaded Joint.

Using the same dimensions, materials, and bolt pattern as in Figure IE 2.2, but this time preloading the bolts high enough to create frictional forces between the joint plates (i.e., at their faying surfaces) such that slip is prevented under the design load of 300 kN (67,500 lbs. force), the procedure first involves computing the slip resistance.

1. Computing slip resistance.

The slip resistance of a shear-loaded joint is given by:

$$R_s = \mu_s F_p b m \tag{2.11}$$

where μ_s is the slip coefficient of the joint, F_p is the average preload in a group or pattern of bolts in kilonewtons or lbs. force, b is the number of shear planes or faying surfaces (as before), and m is the number of fasteners in the joint (as before).

Assuming that the joint surfaces are sandblasted (making $\mu_s = 0.47$), the task at hand is to estimate the average preload, F_p, in the bolts required to develop the needed slip resistance. This is an iterative process. To estimate the average preload, the designer assumes some average pressure is created in each of the bolts involved in the joint. The designer then evaluates the various stresses created in the joint by outside forces, which would cause shear in the fasteners, tensile overload in the joint plates, elongation of bolt holes under bearing, or fastener tear-out at edges, and compares them to the force needed to cause slip in the joint under the assumed value of preload.

In this illustrative example, if the average preload is assumed to be 77.5 kN (17,400 lbs. force) in each of the five bolts in the joint,[10] then the slip resistance is:

$$R_S = \mu_s F_p bm = 0.47(77.5\,\text{kN})(2)(5) = 364\,\text{kN}(81,780\,\text{lbs. force})$$

2. Comparing slip resistance to the loads in the joint.

For Illustrative Example 2.2, with ASTM A325 steel bolts in ASTM A36 steel joint plates where the assumed average preload is 77.5 kN (17,400 lbs. force), the following maximum tolerable loads result for the various allowable stresses:

- The load to exceed the bolt shear allowable = 660 kN (148,200 lbs. force)
- The load to exceed the plate tension allowable = 912 kN (204,800 lbs. force)
- The load to exceed the splice plate bearing allowable = 2, 764 kN (620,600 lbs. force)
- The load to exceed the plate shear allowable = 792 kN (177,800 lbs. force)

Thus, bolt shear determines the ultimate strength of this friction-type joint, but at a load well beyond that imposed in this example.

2.4.5 Axial Shear Versus Eccentric Shear

A joint is not always loaded in such a way that all of the fasteners in a pattern see the same load. In fact, even if all fasteners are the same size and equally tight-fitting and tightened (for bolts or machine screws), and if joints are really perfectly rigid, the load on each fastener will not be the same unless the resultant of all externally applied loads passes through the centroid (center of mass or gravity) of the joint's fastener pattern. When this occurs, the joint is said to be *axially loaded* and the joint is called an *axial shear joint*. When the resultant of the externally applied loads does not pass through the centroid of the fastener pattern, as in Figure 2.15a, a net moment acts on the pattern and each of the fasteners in the pattern resists the resulting moment differently. In such a case, the joint is said to be *eccentrically loaded* and the joint is called an *eccentric shear joint*.

[10] For A325 steel bolts that are 22 mm in diameter, this would result in a tensile stress of 203.9 MPa (29.6 ksi), which is close to the yield strength of these bolts at around 225–250 MPa (32.6–36.3 ksi).

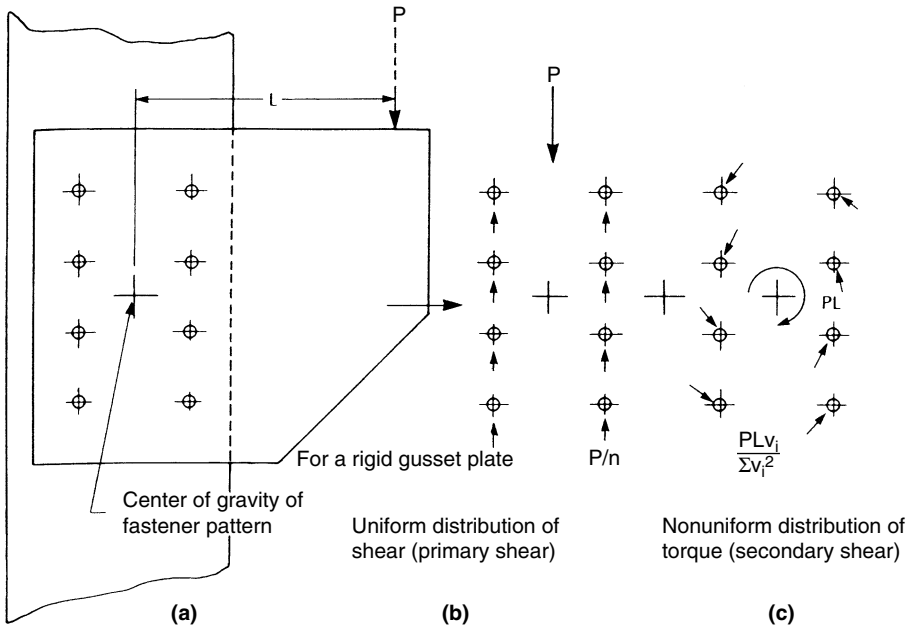


Figure 2.15 Schematic illustration showing an eccentrically (as opposed to axially) loaded shear joint: (a) joint arrangement; (b) primary shear loads; and (c) secondary shear loads (or moments). (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.11, page 43, with permission of Elsevier Science, Burlington, MA.)

Shear-loaded fasteners, of both the bearing type and friction type, are commonly encountered in structural steel construction (e.g., bridges, buildings, and ships) and in riveted airframe structures. Many times the loading in such structures is eccentric. The analysis of an eccentrically loaded joint, is much more involved than for an axially loaded joint, although it is similar in most respects. Without going into great detail, the procedure involves the following steps:

1. Determine the location of the centroid of the fastener pattern with a reference Cartesian coordinate system, $(\bar{x}, \bar{y})$, where:

$$\bar{x} = A_1X_1 + A_2X_2 + \ldots + A_nX_n/A_1 + A_2 + \ldots + A_n \tag{2.12}$$

$$\bar{y} = A_1Y_1 + A_2Y_2 + \ldots + A_nY_n/A_1 + A_2 + \ldots + A_n \tag{2.13}$$

2. Determine the primary shear forces in the fasteners by dividing the applied load by the number of fasteners in the pattern:

$$F_{fastener} = F/m = \text{applied force/fastener} \tag{2.14}$$

3. Determine the secondary shear forces or reaction moment forces in each fastener, using:

$$M = F_1 r_1 + F_2 r_2 + \ldots + F_n r_n \tag{2.15}$$

and

$$F_1/r_1 = F_2/r_2 = \ldots = F_n/r_n \tag{2.16}$$

where r_i is the radial distance of a fastener i from the centroid of the fastener pattern (in millimeters or inches) and combine as:

$$F_n = M r_n/(r_1^2 + r_2^2 + \ldots + r_n^2) \tag{2.17}$$

where n is a given fastener.

4. Combine the primary and secondary shear forces for each bolt by vectorial means (with secondary shears perpendicular to a line drawn from the centroid to any particular fastener).
5. Compute the shear stress in each fastener by dividing the reaction moment force in each fastener by the area of that fastener:

$$\tau = F_n/A_n \tag{2.18}$$

and compare these values to the maximum allowable shear stress for the fastener material.

Viewed another way, an eccentric load on a pattern of fasteners can be analyzed as a combination of a shear force (i.e., the primary shear force above) plus a torsional moment (i.e., the secondary shear force above). This approach is shown in Figure 2.15b and 2.15c. Illustrative Example 2.4 clarifies this latter approach.

Illustrative Example 2.4—Analysis of an Eccentrically Loaded Shear Joint.

Given a joint like that shown in Figure IE 2.4a consisting of eight $\frac{1}{8}$ -in. diameter A490 bolts in A36 steel arranged and eccentrically loaded with a 40 kip (40,000 lb.) downward force at point P located 8 inches from the centerline of the right-most vertical row of bolts, determine the load on the most highly loaded bolt.

The primary shear loads on the bolts in this example act in a vertical direction down, as shown in Figure IE 2.4b. The shear stress per bolt is:

$$40\,\text{kpsi}/8\ \text{bolts} = 5\,\text{kpsi}(5,000\,\text{lbs.})\ \text{per bolt}, \qquad \text{from Equation2.14.}$$

The torque or moment M from Equation 2.15 is shown in Figure IE 2.4b and is:

$$40\,\text{kpsi}\ [8\ \text{in.} + 5\frac{1}{2}\text{in.}/2] = 430\ \text{kip-in.}$$

If in this problem the distance of any bolt i from the center of gravity of the pattern is r_i, , and this is known to be the hypotenuse of a triangle with sides equal to the horizontal and vertical distances of the bolt from the centroid, then values of r_i^2 needed in Equation 2.17 to determine the secondary shear force on each bolt can be determined for all bolts as follows. For the four bolts close to the centroid:

$$r_i^2 = 2^2 + (5\frac{1}{2}\ \text{in.}/2)^2 = 11.56\ \text{in.}^2$$

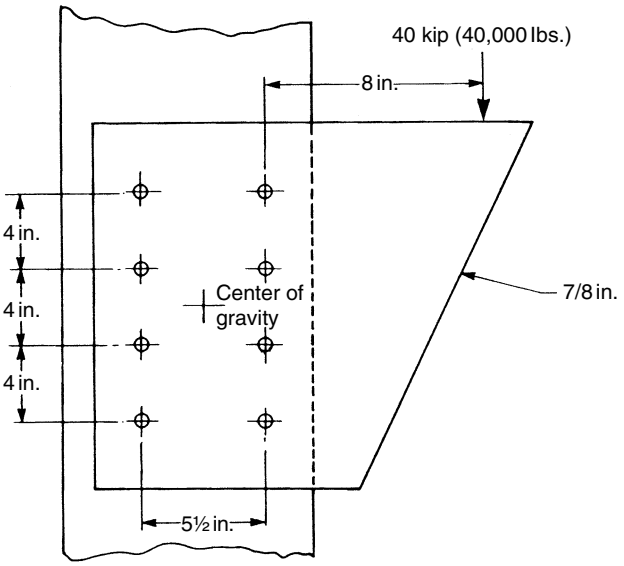


Figure IE 2.4 Schematic illustration of a fully dimensioned eccentrically loaded joint (a) along with primary and secondary shear-induced forces and moments (b) and vector summing (c). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 2.12, page 44, with permission of Elsevier Science, Burlington, MA.)

so the sum of r_1^2s for these four bolts is 46.25 in.^{2}. For the four bolts far from the centroid,

$$r_2^2 = 6^2 + (5\frac{1}{2}\text{ in.}/2)^2 = 43.56\text{ in.}^2$$

so the sum of r_2^2s for these four bolts is 174.25 in^2.

Thus, the vertical and horizontal components of the secondary shear force for the most highly loaded bolt are gotten from Equation 2.17 as:

$$F_{vertical} = Mh/r_i^2 = [430\text{ kip-in.}(2.75\text{ in.})]/(46.25 + 174.25) = 5.36\,\text{kpsi}220.5\text{in}^2$$
$$F_{horizontal} = Mv/r_i^2 = [430\text{ kip-in.}(6\text{ in.})]/(46.25 + 174.25) = 11.72\,\text{kpsi}220.5\text{ in}^2$$

where h and v are the horizontal and vertical distances of the most highly loaded (i.e., the most distant) fastener from the centroid, as shown in Figure IE 2.4b.

The vector sum of all primary and secondary shear components, from Figure IE 2.4b, as shown in Figure IE 2.4c, is:

$$R = [(11.72)^2 + (5 + 5.36)^2]^{1/2} = 15.6\,\text{kpsi}$$

This value compares favorably to the shear allowable for A490, which is 24.1 kpsi, and is therefore acceptable.

2.5 TENSION-LOADED FASTENED JOINTS

2.5.1 Principle of Joint Operation

Many mechanically fastened joints must withstand applied and/or internally generated forces that load the fastener in tension and not shear. The joints designed to accept such loads are called *tension-loaded joints,* an example of which is shown schematically in Figure 2.16. Bolted joints are the best, and probably only, proper example. In bolted joints, the applied and/or internally generated load is usually more or less parallel to the axis of the bolts, and the clamping force developed by the bolts on the joint elements is critical to the joint's performance. The development of a clamping force is called *preloading*. This section discusses these important joints and considers the critical role of preloading in their operation.

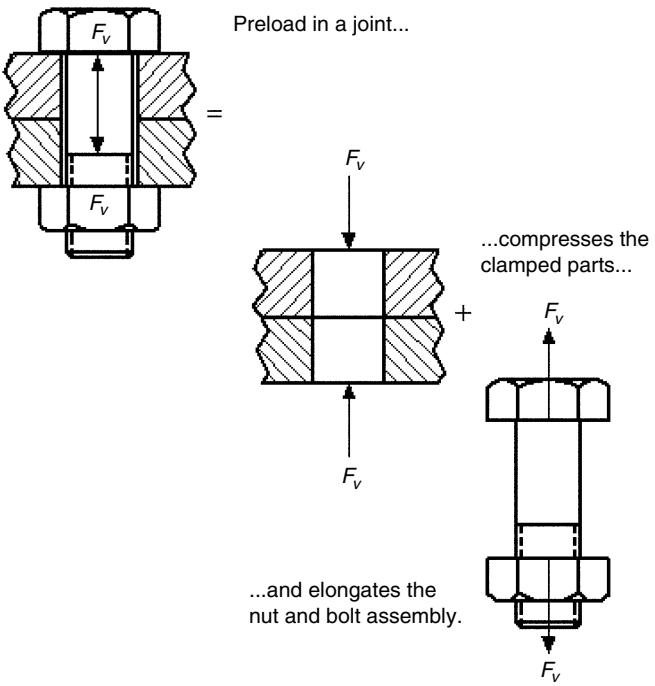


Figure 2.16 Schematic illustration showing an example of a tension-loaded fastened joint; i.e., a bolted split journal on a connecting rod for an internal combustion engine. (Reprinted from *Fundamentals of Machine Component Design*, R.C. Juvinall and K.M. Marshek, John Wiley & Sons, New York, NY, 1991, Fig. 6-10, page 241, with permission.)

2.5.2 The Purpose of Preload

As for all joining methods, strong joints that are intended to provide reliable performance, especially for long service life, require thorough analysis of all of the known or possible (i.e., reasonably expected) forces on the joint (see Chapter 1, Subsection 1.7.1). This is obviously also true for bolted connections, but familiarity with such connection sometimes leads designers to think thorough analysis is not necessary. Nothing could be farther from the truth!

The fact that certain threaded fasteners, like bolts and their smaller cousins, machine screws, are capable of easily and reliably developing a clamping force on a joint makes these fasteners ideal for creating tension-loaded joints. By tightening a nut onto a bolt or machine screw or by tightening a bolt or machine screw into an internally threaded back-side joint member, all joint members are subjected to an initial clamping force known as a "preload." This preload must be high to compress the joint structural elements, thereby improving the resistance of the joint to externally applied tensile loads. Resistance to shear loads is also improved by this same clamping force as it creates friction between the joint elements (see subsection 2.4.1). However, recalling that, for there to be mechanical equilibrium, tensile forces must be offset by compression forces, it should come as no surprise that to produce a compressive clamping force (or preload) in the joint requires that a tensile preload must exist in the fastener. The preload in the fastener is commonly called the "working load". Thus, it follows that the amount of clamping force must be limited so that the combination of fastener tensile preload and externally imposed tensile load on the fasteners holding the joint together lead to the fastener's working load that must not exceed the yield-point load limit (i.e., yield strength) of the fastener. If it does, the fastener and the joint are on their way to failure.

To allow preload to work to advantage for the joint in compression without working to the disadvantage of the fastener in tension, so-called *bolted joints* are (or should be!) designed so that the clamped joint elements are much stiffer than the fastener is. When this is true, the compressive preload in the joint can be high, while the bolt tensile working load can be relatively low. Low tensile working load is desirable to reduce the likelihood of fatigue in dynamic applications, whether in static or dynamic structures.

Basic mechanics and strength of materials tell one that the magnitude of the applied force (i.e., the preload) and the relative stiffnesses of the clamped joint elements and fastener(s) determine the resulting deflections. This can all be shown schematically by plotting the stiffness characteristics of the fastener and the clamped joint elements in a load/deflection diagram, as in Figure 2.17a. Load versus deflection behavior is linear because the fastener and the joint elements should be operating within the elastic region of their respective materials.

In Figure 2.17a, the stiffness characteristic[11] for the bolt (or machine screw), commonly designated k_s, is plotted with a positive slope, whereas the stiffness characteristic for the clamped joint, commonly designated k_p, is plotted with a negative slope.

[11] The *stiffness characteristic* for a bolt and for clamped joint elements is complicated; involving more than simply the bolt or joint element materials' elastic moduli. Geometric factors and fit (which affect compliance in the joint) are also important.

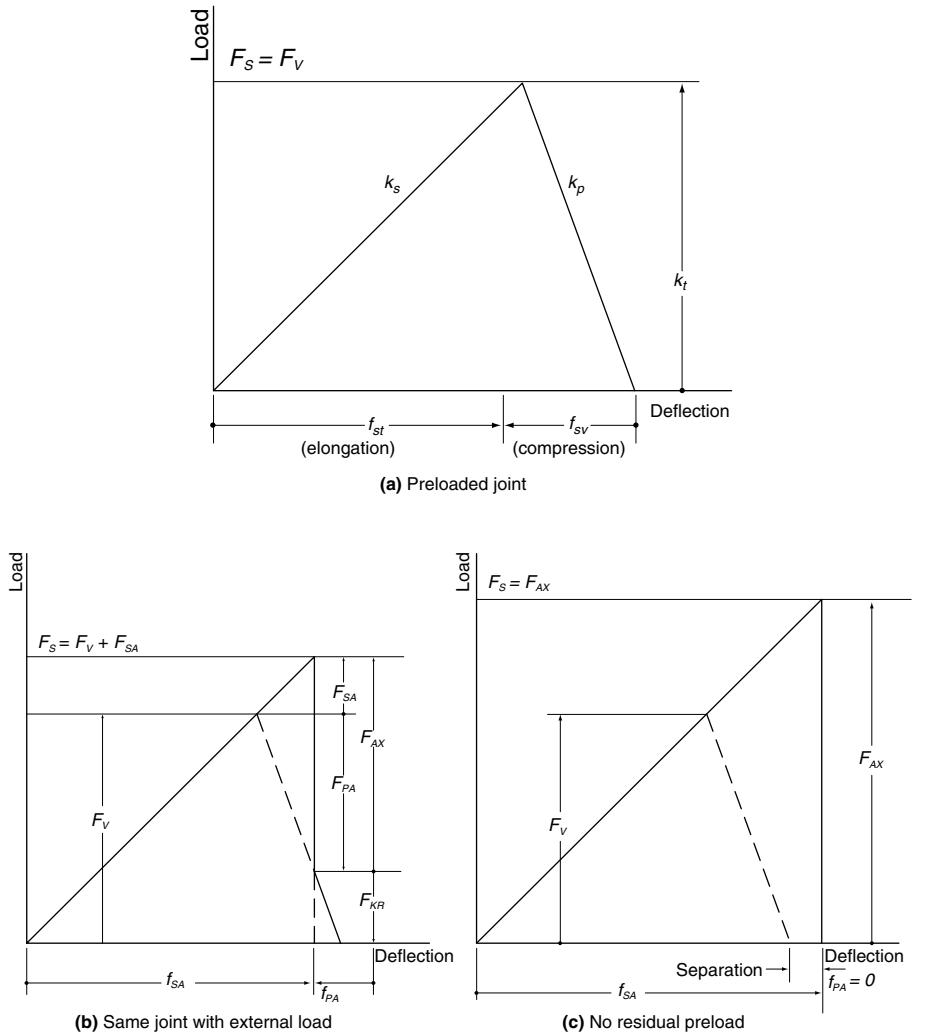


Figure 2.17 A schematic plot of the load-deflection behavior of clamped joint elements in a tension-loaded joint, showing: (a) the stiffness characteristic of the bolts (given by k_s) and of the joint itself (given by k_p), (b) what happens when an external tensile load is applied, and, finally, (c) what happens when the applied tensile load causes joint separation. (From ''Analyzing critical joints,'' by S.F. Aaronson, *Machine Design*, January 1982, 95–101, with permission.)

Normally, a bolted joint is designed so that $k_p > k_s$. When this is the case, the stiffness characteristic of the clamped joint elements is steeper than that for the bolts. When the joint is preloaded, it compresses by what is commonly given as f_{pv}, while the bolts elongate by an amount commonly given as f_{sv}. This is shown schematically in Figure 2.17b. Not surprisingly, the stiffer clamped joint elements actually deflect less than the bolt does.

When an external tensile load, commonly designated as F_{AX} is imposed on the preloaded joint, the bolts elongate and joint element compression decreases. The resulting deflections (shown in Figure 2.17b) are commonly labeled f_{SA} and f_{PA}, respectively; with $f_{SA} > f_{PA}$ in most cases. And here's the key: If the clamped joint elements are stiffer than the bolts are, only a small fraction, designed F_{SA}, of the external load F_{AX} is added to the load in the bolts F_S. The balance of the external load, F_{PA}, is resisted by the clamped joint elements. So, as long as F_{SA} can be kept small, then fatigue loading on the bolts will also be low.

This "good news" does not go on forever, however. External load cannot be applied to a joint without limit. Higher and higher applied tensile loads reduce the compressive load in the clamped joint elements more and more. When all of the compression is removed, the clamped joint elements separate; at which point the bolts must carry the entire external load, so $F_S = F_{AN}$. Thus, a bolted joint usually requires a certain amount of residual clamping load, commonly designated F_{NX}, to keep the clamped elements from separating. This residual load, like the other loads, can be calculated. Figure 2.17c shows the situation when joint elements separate.

2.5.3 Procedure for Determining Appropriate (Target) Preload

To be assured that strong and reliable bolted joints result, the initial or "target" clamping load or joint preload and the bolt working load must meet four basic requirements:

1. The maximum clamping load must be greater than the required nominal preload to allow for embedment (see subsection 2.5.7) as well as to offset expected scatter in tensioning (see subsection 2.5.4); i.e., $F_{M(max)} > F_V$, as shown in Figure 2.18.
2. The magnitude of the above maximum clamping force must be no greater than 70% of the 0.2% offset yield point of the fastener material; i.e., $F_{M(max)} < 0.7F_{0.2}$.
3. The bolt working load must be no greater than 10% of the 0.2% offset yield load; i.e., $F_{SA} < 0.1F_{0.2}$.
4. The bolt working load must also not exceed the endurance limit load for the bolt if fatigue is a consideration; i.e., $F_{SA} < F_E$.

These and other key loads are shown schematically in Figure 2.18, with the following terms:

$F_{M(min)}$ = Minimum acceptable clamping load (lbs. force or kN)
$F_{M(max)}$ = Maximum clamping load (lbs. force or kN)
F_S = Total bolt load (lbs. force or kN)
F_X = Load allowance for embedment (lbs. force or kN)
F_{SP} = Clamping load limit (lbs. force or kN)
$F_{0.2}$ = Load at 0.2% offset yield point (lbs. force or kN)

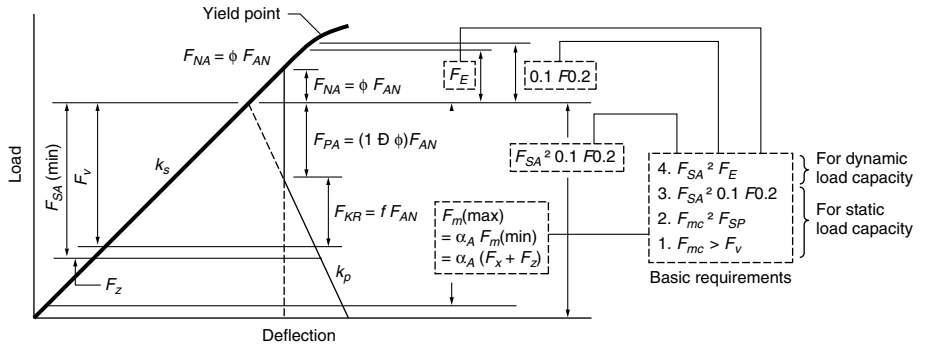


Figure 2.18 Schematic illustration showing the key loads occurring in a preloaded (clamped) joint. (From "Analyzing critical joints," by S.F. Aaronson, *Machine Design*, January 1982, 95–101, with permission.)

F_E = Bolt endurance load (lbs. force or kN)
F_{SA} = Bolt working load (lbs. force or kN)
F_{PA} = Clamped joint element working load (lbs. force or kN)
F_{AN} = Effective external load (lbs. force or kN)
F_{NR} = Residual clamping load (lbs. force or kN)
ϕ = Theoretical resiliency ratio
f = Residual load factor
k_s = Bolt stiffness (lb./in. or kN/mm)
k_p = Clamped joint element stiffness (lb./in. or kN/mm)

The procedure for calculating the proper clamping preload is covered very well and very thoroughly in Aaronson (1982) and therefore will not be covered here. This fine paper also introduces the critical concepts of *tightening factors* (to account for scattering in tensioning by torque), *joint resiliency* (which depends on material type and clamping ratio, and relates to "stiffness" of the joint), and *residual load factor* (used in calculating the residual clamping load needed to assure joint elements do not separate under external tension).

Without going into great detail here, the analysis required to determine the appropriate level or "target" preload involves the following steps, some of which are analytical, some of which are empirical, and some of which involve experimental measurements:

1. Estimate the external (as well as any internally generated) loads seen by the bolted joint, including static (tension, shear, bending, torsion), dynamic (fatigue, impact, seismic), and inertial loads.
2. Compute the stiffness or spring rate of fasteners, k_s, using an empirical relationship such as

$$k_s = A_a A_B E / L_s A_B + L_B A_s \tag{2.19}$$

where the various parameters relate the areas of the threaded and unthreaded portions of the bolt, the threaded and unthreaded lengths of the bolt, and the bolt material's modulus of elasticity.

3. Determine the joint's stiffness, k_p, experimentally by applying an external tension load to the fastener and measuring the tension load in the fastener with a strain gauge or ultrasonically. Then, when the stiffness of the bolt is known (from these tests), a technique known as "joint-diagram," which relates to the load-deflection diagrams for the bolt and joint materials, is used to estimate the joint stiffness. Alternatively, plots of joint resilience can be employed and parameters needed for calculating preload can be determined graphically.
4. Select a target preload, which is generally the greatest load (known as the "allowable upper limit" or $F_{M(max)}$ as used earlier) that the bolt can withstand without yielding, accounting for torque (e.g., from nuts) and other loads (e.g., shear, bending), but considering the "acceptable lower limit"[12] or $F_{M(min)}$ (as used earlier) to prevent failure by leaking, vibrating loose, or shortening needed fatigue life.
5. Determine whether or not the tension normally developed in any bolt will exceed the maximum allowable tensile strength for the particular bolt material. Here, assembly tool (e.g., torque wrench) errors and operator problems (e.g., skill level, worker fatigue, bolt accessibility) must be taken into account by adding to the preliminary target preload.
6. Consider actual lower limits on clamping force brought about due to relaxation effects (e.g., plastic flow in bolt threads or in new parts), often called "embedment relaxation" and/or elastic interactions between bolts (e.g., the effect of tightening sequence) (see Subsection 2.5.7). These effects must be subtracted from the preliminary target preload.

From all of the foregoing, it should be obvious that the procedure for determining a target preload is involved and imprecise (although it is improving), relying on a combination of analytical, empirical, graphical, and experimental means. More complete descriptions of the procedure, as well as numerous illustrative examples, are given in references by Shigley (1977), Bickford (1983), Shigley and Mischke (1986), and Bickford (1995).

2.5.4 Bolt Torque

Although torque (i.e., tightening threaded fasteners with some kind of driving tool such as a wrench) is the common way to install a bolt or machine screw, it is not a good way to control the preload needed to allow these tension-loaded fasteners to function properly. A particular level of torque tightening can cause $\pm 30\%$ or more scatter in that preload obtained (see Table 2.5). The torque-preload interaction is imprecise because it is affected by many things, including (1) the finish of the threads of the

[12] The acceptable lower limit can be particularly difficult to estimate. It can be zero but is usually 60% of the acceptable upper limit.

nut and bolt; (2) the fit between male and female threads (3) the finish of the joint members at their faying (or mating) surfaces; (4) the size (i.e., tightness) of holes and their perpendicularity to the joints; (5) the hardness of all parts (fasteners and joint elements); (6) the speed of tightening; and (7) the age, temperature, quantity, condition, and type of any lubricant used, if any.

In general, such things as those listed above cannot be controlled very well, no less perfectly, in most applications, and, further, the economics of the assembly situation will often simply not permit enough control to guarantee the desired results. The objective of many modern tightening devices, therefore, is to develop a technique that either directly measures the preload or yields a better correlation between the applied torque and the preload.

When torque is used to tighten a fastener, like a bolt or machine screw (with or without a nut), the correct torque is usually selected from the so-called "short-form torque equation," given in the *Standard Handbook of Machine Design* as

Table 2.5 Typical Scatter in Preload for Various Threaded Fastener Tightening Methods*

Control Parameter and Type of Tool	*Reported Scatter in Preload, as %*
Torque control with	
Hand wrench	±21 to 81
Hand wrench with torque multiplier	±70 to 150
Dial or click wrench	±60 to 80
Wrench with electronic readout	±40 to 60
Power wrench (air or electric)	±23 to 28
Air wrench with one-shot clutch	±30
Air wrench with torque feedback	±20
Stall torque air wrench	±35
Torque-turn control with	
Computer, yield-controlled air tool	±8
Turn-of-the-nut procedure (with steel)	±15
Logarithmic rate method	±2.2 to 2.6
Torque-angle method	±25
Miscellaneous methods	
Strain-gauged bolts	±1
Strain-gauged load washers	±15
Swaged lock-bolts	±5
Bolt headers	±15
Air-powered impact wrench	−300 to +150
Hydraulic tensioner	±20
Skilled operator's feel	±35
Angle method	±15
Fastener elongation	±3 to 5
Ultrasonic control of preload	±1 to 10

*Table adapted from J. Shigley and C. Mischke, *Standard Handbook of Machine Design.* New York, McGraw-Hill, 1977, with permission.

$$T = kd\ F_{PT} \tag{2.20}$$

where k is an experimentally determined constant, known as a "bugger factor," which defines the relationship between the applied torque and the achieved preload in a given situation, d is the nominal diameter of the bolt or machine screw (in mm or in.), and F_{PT} is the target preload (in kilonewtons or lbs. force).

2.5.5 Achieving a Desired (Target) Preload in Bolts

In most cases, the target preload or clamping tension selected for a bolt is achieved by using a wrench of some sort to apply torque to the nut or the head of the bolt or machine screw, on the premise that this applied torque correlates closely with the induced tension. The problem, as stated above, is that there is considerable scatter in the value of the preload obtained for any particular given torque value. Table 2.5 shows how severe this scatter can be for various tightening methods. Because of the importance of preload in the performance of a bolted tension-loaded joint, methods have long been sought for tightening that reduce this scatter in the preload values.

What is surprising is that, for a process as ubiquitous as bolting, so little attention has been given to how such joints operate and how fastening by bolts can be improved. But, as more and more manufacturers realize the importance of optimum clamping, new fasteners, special washers, specialty adhesives, and a variety of tightening systems have emerged. Not surprisingly, the biggest market niches are in critical applications in engines, axles, and transmissions in the automobile industry, in engines and flight-critical primary airframe structure in aircraft and spacecraft, and in pressure vessels of all kinds.

Preferred methods for achieving precise values of preload do so by inducing the preload by literally and directly stretching the bolt, directly measuring the stretch induced by some method of torsional loading or tightening, or directly measuring the clamping force with special bolts or washers or bolt-washer assemblies. Some other methods still rely on developing preload indirectly by torquing, without making any direct measurements. Four methods commonly used are (1) turn-of-the-nut control, (2) microprocessor-controlled torque-turn tools, (3) hydraulic tensioners and bolt headers, and (4) ultrasonic control devices.

The turn-of-the-nut control technique, used extensively with bolting structural steel on construction sites, tightens the nut to produce a preload value that is 60 to 80% of the yield strength of the bolt by using an air-powered impact wrench with a torque-limited clutch. The nut is marked and then turned another half turn to cause yielding in the bolt. The technique is rather imprecise since it is still subject to the same sources of scatter in preload as other torque tightening techniques—it relies on a predetermined correlation between bolt tension and applied torque. Scatter is reduced, however, by going to very high levels of torque.

Microprocessor-controlled torque-turn tools again rely on predetermined correlations between induced tension and applied torque but reduce scatter by more precisely controlling the applied torque. These devices measure both the applied torque and the angle through which the nut turns (i.e., angle methods) to monitor and control fastener preload.

Hydraulic tensioners or bolt headers and ultrasonic control devices directly control and measure the stretch induced in the bolt by tension, respectively. Hydraulic tensioners or bolt headers stretch a large bolt from the threads to a desired preload based on actual extension. Then, having achieved the desired tension, they run down (i.e., "snug") the nut. Ultrasonic devices control tension in the bolt by directly measuring the effect of tightening on the time of flight of an ultrasonic signal caused by the increased length of the tensioned bolt shank and/or velocity changes to the ultrasound wave caused by the presence of residual stresses.

In addition to these methods, some other interesting techniques are used for installing high-strength steel bolts in steel construction. These include so-called "calibrated washers" and/or "calibrated bolts." Calibrated washers have diametrically opposed bumps on each face that deform under the appropriate bolt preload (or squeezing force). Calibrated bolts have a small protrusion at their shank end that breaks off when the proper preload value is reached or a spring-like, fluted (or warped) integral collar under the bolt head that deforms elastically to become flat against the joint element when the proper preload is attained.

A final key to many techniques is providing proper and consistent lubrication; whether in the form of liquids or solid dry films (Bickford, 1983).

2.5.6 Measuring Residual Preload

As if estimating the initial preload in a clamping type fastener by measuring the amount of torque applied during its installation were not difficult enough and of questionable reliability because of the variables involved, measuring the residual preload some time after tightening is even more difficult. Yet, it is important to know if there has been any loss of preload in service because of the importance of such preload to the joint's continued performance and because there are many ways in which losses can occur, as will be described in the next subsection.

For all intents and purposes, it is virtually impossible to measure residual preload by measuring the torque required to re-start fastener rotation, or so-called "breakaway" torque on previously tightened fasteners. The primary reasons are the large uncertainties of the starting friction (or "stiction") at typical preload levels and because it is essentially impossible to tell when re-start or breakaway truly occurs. Visible motion and noise, two obvious bio-feedback indicators, have been shown by strain-gage studies to be unreliable indicators. Thus, better methods are needed, and ultrasonic methods seem to offer the most potential.

Residual preload can be measured in two basic ways using ultrasonics. The first, best, and easiest is to use ultrasonic methods to control the initial tightening, keep a permanent, retrievable record of the initial acoustic length of each critical fastener after tightening, and re-measure each fastener's length after periodic times in service. An estimate can be made of the stress levels remaining in the fasteners, regardless of how much time has passed since initial tightening, by comparing initial and current acoustic lengths. The premise, and requirement, for this method to work is that service temperatures must not be so high that they cause any relaxation of stress in the fastener's

material. The second method is for assessing the preload in fasteners that were not initially tightened ultrasonically. Here, ultrasound is used to measure the length of fasteners before and after loosening. The decrease in length is a good measure of the level of preload that was in the fastener before loosening. By checking one fastener at a time, and restoring the preload (or retightening) before moving on, measurements can be made for all fasteners without disturbing the overall joint. The obvious shortcoming of this approach is not knowing what the initial preload was and, thus, how much loss of preload may have occurred.

2.5.7 Loss of Preload in Service

At least five mechanisms have been identified by which the initial preload in a tightened fastener can be lost in service. The first mechanism is *embedment relaxation*. Upon initial tightening of a newly installed, previously unused threaded fastener (i.e., bolt or machine screw), only the high points of the mating (or engaging) male and female threads and of the joint member's surface contact one another. These high points are therefore overloaded well past their yield points, and so plastic deformation by continued anelastic strain or creep mechanisms occurs until a large enough percentage of the available contact surfaces has been engaged to stabilize the process. Such plastic flow occurs in thread roots (where the small radius gives rise to a severe stress concentration), in the innermost bolt threads that engage nut or threaded part threads, under the faces of the bolt head or nut (especially if the bolt is not exactly perpendicular or normal to the joint), and at the corners of the bolt heads or nuts. As a result, losses of 5 to 10% of the initial preload are not uncommon, and losses up to 25% are possible. Embedment cannot be avoided in most newly manufactured or assembled parts, but it can be partially overcome by installing the fastener, loosening it to the point of removal, and retightening it. This, at least, removes the worst "burrs" or high points.

The second source of loss is *gasket creep*. When gaskets are used to seal a fastened joint against fluid leakage or infiltration (as must be done with fasteners because they cause joining with only mechanical forces, not chemical or physical forces, as explained in Chapter 1), they invariably relax over time. This occurs because, to work effectively, gaskets are intentionally made of compliant materials (e.g., cork, felt, rubber, plastics, or soft metals, such as lead or copper). At least, polymeric materials, because of their structure (which involves secondary bonding between twisted, kinked, and tangled long-chain molecules) inevitably relax over time under loading as a result of viscoelastic flow. In fact, such flow is necessary for the gasket to work properly (i.e., to seal itself). Nothing can be done to avoid gasket creep or to compensate for it during initial fastener tightening. But, it can be compensated for later by retightening.

The third source of preload loss is *elastic interactions*. In the process of tightening a group of fasteners in a pattern, there are inevitable elastic interactions among the various fasteners because of joint compression.[13] After the first bolts or machine

[13] *Joint compression* refers to the squeezing together of imprecisely or imperfectly fitting joint elements, not compression of the materials in the joint elements themselves.

screws are tightened, the joint compresses and the fastener feels to be or measures tight. When an adjacent fastener is installed and tightened, however, the joint is further compressed, and the preload in the first fastener is partially or totally lost. This process goes on throughout the fastener installation and tightening process. Losses of 40 to 50% are common and up to 100% are known. Tightening fasteners in a sequence that attempts to balance joint compression throughout tightening, retightening during a second (or subsequent) pass, or even overtightening the first fasteners are all methods that can be used to compensate for elastic relaxation. Often, a so-called "star pattern" is used to tighten bolts and/or nuts on a so-called "bolt circle".

Embedment relaxation, gasket creep, and elastic relaxation are all fairly short-term sources of loss of preload. Two other sources take longer to occur. The first is *vibration loosening*. Under the action of vibrational loads, threaded fasteners often loosen, unless special precautions are taken. Under severe vibration, the fasteners first lose preload gradually over time. Once the preload has fallen so far that it is no longer able to prevent transverse slip between male and female threads or bolt head or nut and joint surfaces, then the loosening action accelerates rapidly and can result in the complete loss of the nut or the bolt or machine screw or both. For vibration that is parallel to the axis of the fastener, 20 to 40% loss of initial preload is typical, but for vibration that is transverse to the axis of the fastener, complete loss can readily occur. Unlike the short-term loss mechanisms, vibrational loosening can be prevented by properly designing the joint, choosing a fastener that can be preloaded high enough to prevent transverse slip, or choosing a fastener design or fastening system that inherently resists or a device that prevents vibrational loosening. Special thread forms, so-called "locking" adhesives on the threads, use of spring-nuts or lock-washers, and wiring of nuts to bolt shanks can all help.

The second source of long-term loss of preload is *stress relaxation*. When fasteners are used in applications where the service temperature is extreme relative to the fastener material's absolute melting or softening point, or where there is nuclear radiation, the atoms in the fastener material can realign in areas of stress by a process related to creep, and stress relaxation of the preload occurs. The only way to avoid this long-term effect is to use fasteners made from materials that have a resistance to it.

A final cause of threaded-fastener loosening can be rotating motion of the assembly containing the fasteners. Lug nuts on threaded wheel hubs can loosen just from the direction of the wheel's rotation in service. To preclude this, some automobile manufacturers, and some machine tool builders use fasteners that are threaded in the opposite direction from normal (i.e., "left-hand" threads).

2.6 FATIGUE LOADING OF FASTENED JOINTS

2.6.1 Sources and Signs of Fatigue Loading

One of the most common and problematic types of loading is repetitive or cyclic loading. Such loading is known as *fatigue loading*. It is present in every dynamic structure and in many, if not most, static structures. Fatigue can arise from highly

repetitive and highly predictable sources, such as from repetitive motions in the assembly or structure, with an excellent example being the various loads associated with the various stages of combustion in a four-cycle or a two-cycle internal combustion engine. It can also arise from less predictable but still highly repetitive sources, such as motion-induced vibrations (and, at its worst, resonance and aero-elastic fluttering), or shaking associated with improperly balanced rotating, mechanisms. It can also arise from more erratic but repeated loading, such as various g-loadings during high-speed turns during maneuvers in aircraft or motor vehicles, or from takeoffs and landings in aircraft, and bumps negotiated by cars and trucks. Loading rates can be high frequency or low frequency and high stress or low stress, fully periodic or random, sinusoidal, square, or seemingly random in waveform. But, what all have in common is that such loading in a structure gives rise to damage known as "fatigue" in the material(s) from which the structure is produced.

Regardless of its source, fatigue leads to sudden and unexpected joint failure, usually by breakage, and it is the most common cause of all failures (with corrosion being a close second).[14] The performance of a structure subjected to fatigue (often measured by the structure's life in terms of the number of loading cycles until failure) is highly sensitive to part design and inherent stress concentrations and is dependent on the level of stress, or "stress intensity." Fatigue life increases, all else being the same, as the stress intensity is lowered. The nature of fatigue is such that failure can occur at stress levels below the accepted static-yield strength level.

The same basic principles of design employed for static tension-loaded joints apply to tension-fatigue-loaded joints. Adequate preloading is the prime factor necessary to meet or exceed anticipated cycling loading on the joint. A properly tightened and preloaded bolt or machine screw will experience only minimal external tensile forces imposed by repetitive tensile loading (see Subsection 2.5.2). The stresses expected during service must be carefully defined in proper designs and may involve detailed experimental testing and simulated service conditions beyond just careful and complete analysis. This can be difficult, not just time consuming and expensive. In any case, as a result of the typical stress versus number of loading cycles (or S-N) curve relationship exhibited by fatigue, the allowable design stresses that have to be used for safe operation of joints of this type are substantially lower than those for comparable static-loaded joints, especially, where long service life is required. After all, as the name seems to imply, a structure, and the material from which it is constructed, accumulates damage and becomes tired, if you will. This is illustrated in the plot shown in Figure 2.19.

While the precise time failure from fatigue will occur is difficult, if not impossible, to predict, there are several clues that failure may occur or has occurred from fatigue, including (1) If cyclic (especially tensile) loads were present during service, whether planned or accidental; (2) If there was no warning of the onset of the eventual failure by localized necking, plastic stretch marks, or obvious wear; (3) If the rough appearance of the fracture surface(s) where overload occurred contains a smooth

[14] Actually, the mechanism of fatigue in a material involves nucleation of a crack and then propagation of that crack until failure by overload occurs. Actual initiation can take a long time, and growth can be slow or fast, depending on the material, load level, environment, etc.

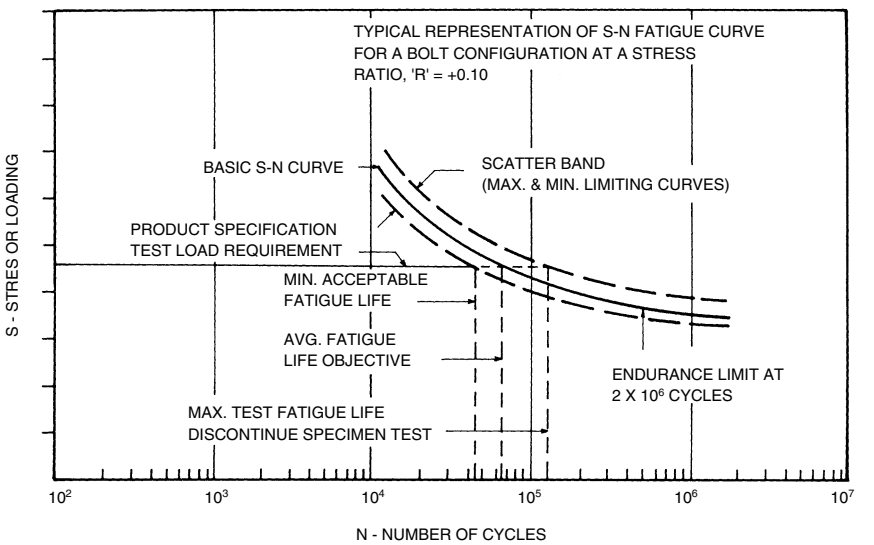


Figure 2.19 A typical representation of the S-N curve for a fatigue-loaded fastener. (Reprinted from *Standard Handbook of Fastening and Joining*, 2nd edition, Robert O. Parmley, McGraw Hill, New York, NY, 1989, Fig. 1.11, page, 1–14, with permission.)

(almost polished) appearance where fatigue was causing slow crack propagation, possibly with tell-tale striations or crack arrest marks; and (4) If failure appears to have initiated at points of high stress concentration at surfaces from things such as (a) sharp radii on joint elements or fasteners (e.g., under heads), (b) machining marks or gouges on the fastener or joint elements, (c) at thread run-out areas on bolts or where bolt threads just engage a nut or internally threaded joint element, (d) in areas of wear or fretting in friction-type joints, or (e) where a joint splice plate or "doubler" or section change ends. Figure 2.20 schematically illustrates some of these sources of fatigue.

2.6.2 Reducing the Tendency for Fatigue Failure

While in most materials it is impossible to completely avoid or prevent fatigue, it is possible to reduce the likelihood of fatigue within the needed service life of a structure or assembly by the combination of proper design, proper analysis, and proper manufacturing, not to mention proper use![15] This subsection discusses some of the things that can be done to reduce the tendency for fatigue failure.

First, select materials carefully. Materials with higher tensile yield strength (and/or larger differences between their tensile yield and ultimate tensile strength) have

[15] It must be recognized that fatigue is a stochastic process, prone to the vagaries of statistics. Thus, precise prediction is never possible.

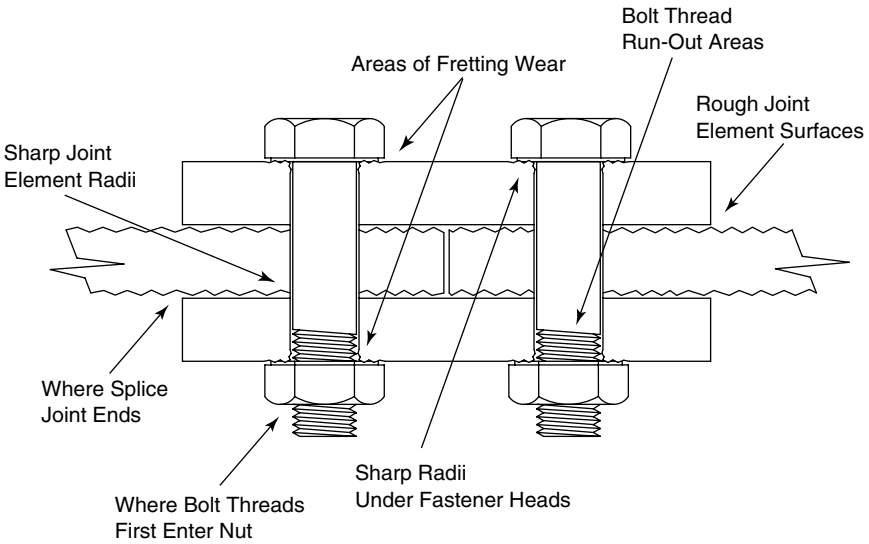


Figure 2.20 Schematic illustration showing some of the sources of fatigue in a bolted joint.

longer fatigue lives than materials with lower tensile strengths (and/or smaller differences between their tensile yield and ultimate strength). For such materials, it is generally easier to operate the material at a lower proportion of its yield or ultimate fatigue strength. In addition, some materials (e.g., face-centered cubic metals and alloys, polymers above their glass transition temperatures) have inherently lower notch sensitivity (as measured by their crack growth rate, da/dt or da/dN; that is, the incremental growth of a crack by an amount a, per increment of time t or per loading cycle N). Some materials, such as wood, seem inherently immune to fatigue, and others, like cement and concrete, are not plagued by fatigue because they are subjected only to compressive loads and stresses, or, at worst, only very modest tensile loads or stresses. Finally, materials should be treated to avoid potentially degrading reactions or transformations during processing, such as decarburization and/or untempered martensite formation (e.g., during welding of steels), as these can increase susceptibility to fatigue by lowering strength or ductility.

Second, treat all parts and joints with care. No matter how carefully a part or joint is designed, and no matter what the materials used are, careless manufacture or abusive operation can lead to problems in fatigue. In fastened assemblies or structures, nut faces and the under-surfaces of bolt heads must be perpendicular to the fastener axis, and the fastener hole must be perpendicular (or normal) to the joint element. A $\pm$ 2% error in angularity can reduce fatigue life by 25%. In bolted joints, the threads of the bolt or machine screw (and/or nut) should be lubricated to prevent corrosion as a source of cracks. For friction-type joints, faying surfaces should be grit blasted to increase slip resistance, since increasing the slip resistance increases the joint's fatigue life.

Third, do everything possible to prevent crack initiation at surfaces. Fatigue initiates at the surface of a material or a part, so special care should be given to the

surface during fabrication and in service. Machining (or "kerf") marks, handling scratches or gouges, and other surface blemishes should be removed by polishing (or other finishing processes) in areas of potential fatigue or high loading (e.g., edges, section transitions, holes, etc.). A part's surface can be further protected by introducing compressive residual stresses to offset any cyclic tensile loads. Shot peening, burnishing, and roll-forming or planishing are preferred methods for doing this. To further protect the surface, corrosion should be prevented by any possible means (e.g., using paints, lubricants, surface conversion coatings, or platings—provided conversion coatings or platings are not themselves brittle or embrittling).

Fourth, attempt to reduce load excursions as much as possible. Several things can be done to reduce fatigue by reducing the severity of load excursions. Keep the ratio of the minimum to the maximum load as near to unity as possible; avoid high tensile loads, and in particular keep preload high compared to the worst-case external load and keep the ratio between the stiffness of the joint and the stiffness of the bolt or machine screw high. This latter trick allows the joint to absorb the larger portion of the applied loads. And, make every effort to maintain the preload against losses (see Subsection 2.5.7).

Finally, among the ways for improving the fatigue life of mechanically fastened joints is to reduce the stress and, especially, the stress concentrations in the fasteners themselves. Methods include ensuring that there are at least three threads above and three threads below or within a nut face or internally threaded part's surface; avoiding having the thread run-out coincide with a shear plane in the joint; using large head-to-body fillets; using a large thread root radius; using rolled-in rather than cut threads; using collars between the head and the joint plates and between the nut and the joint plates to increase the length-to-diameter ratio of the bolts; turning down the diameter of the bolt body just below the head to reduce the bolt's stiffness relative to the joint's stiffness; using long or thick nuts; using spherical washers to help a bolt adjust to bending loads; and using so-called "tension nuts" to reduce the level of stress in the threads.

In summary, consider fatigue carefully in the design and manufacture of all mechanically fastened joints.

2.7 OTHER FACTORS AFFECTING FASTENERS AND FASTENED JOINTS

Many other factors besides fatigue need to be considered when employing fasteners for joining. These include bending loads, vibration, and corrosion, to name a few of the more important ones.

2.7.1 Bending Loading

Structural joints are seldom loaded in pure tension or compression or shear. Even when they seem to be at the design stage, actual service frequently reveals that other types of loads, most notably bending loads, are operating. Bending in what appears to

be a pure tension- or shear-loaded joint can come about from anything that caused the actual load to develop any eccentricity, including manufacturing tolerance build up; in-service, warpage, or other distortion; or unexpected loads from unexpected sources. For applications where bending-load conditions are expected, the design limits for the fasteners used in joints must be established from what are known as "interaction curves." These are developed from actual tests in which a number of bolts are evaluated under different combinations of applied tensile and shear loadings. From such a curve (as shown in Figure 2.21), it is possible to calculate the maximum allowable design stresses for tension and for shear for any particular degree of bending. Even when carefully developed interaction curves are used in a design analysis, however, additional caution must be exercised when bending loading is expected. Bending loads increase stress concentration effects at notches, such as thread roots, thread run-outs, and fastener head-to-shank radii.

Even worse, bending can drastically change the way in which the joint acts and the fastener must behave. Examples are (1) bending introducing tension into fasteners intended for what were supposed to be shear-loaded joints operating in bearing; (2) bending introducing tension out of the plane of a shear-loaded joint intended to operate with fastener-induced friction; and (3) bending causing joint opening between fasteners used with seals or gaskets, creating leaks.

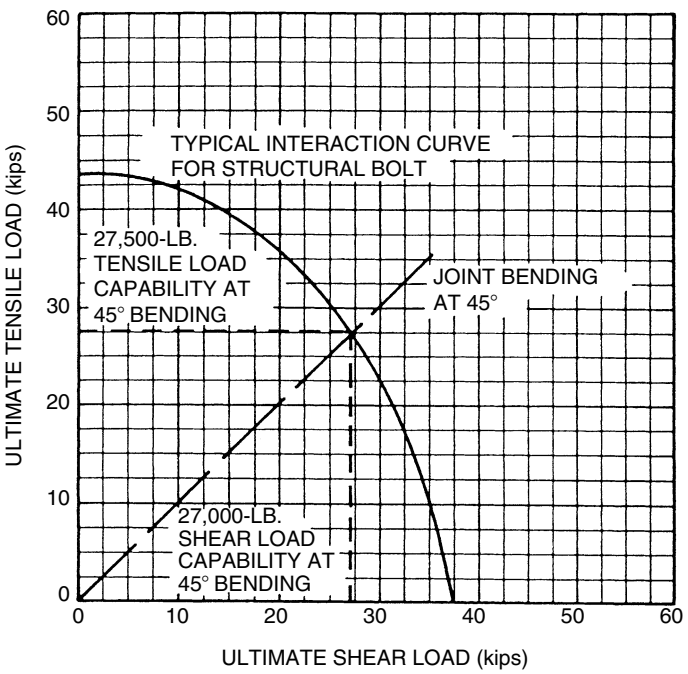


Figure 2.21 A typical interaction curve for fasteners subjected to bending loading; combining tension and shear loading. (Reprinted from *Standard Handbook of Fastening and Joining*, 2nd edition, Robert O. Parmley, McGraw Hill, New York, NY, 1989, Fig. 1.14, page 1–21, with permission.)

2.7.2 Vibration Loading

Vibration in a structure can obviously lead to fatigue at joints, as vibrations are inherently cyclic. However, while the loading produced by vibration is usually low in magnitude compared to the strength of the fastener, it can occur at several frequencies or over a range of frequencies that changes as whatever is causing the vibrations in the first place changes. Unless the frequency, loading, and amplitude of vibrations cause resonance in the structure (by matching the structure's natural frequency, or one of its harmonics), catastrophic failure by fatigue due to vibration rarely occurs. Nevertheless, vibration can cause problems. The more common problems arising from extensive or continued vibrations cause loosening of tightened threaded fasteners (see Subsection 2.5.7). The actual mechanism by which small translations from vibrations lead to forces that can cause a threaded fastener (i.e., bolt, machine screw, or nut) to loosen by rotation is complex, and the results can be serious. Nuts literally "walk off" a bolt, preloading in a bolt or machine screw can be lost, which subjects the joint elements to loads they were not intended to have to deal with, or bolts or machine screws can literally fall out.

2.7.3 Corrosion and Environmental Degradation

It is well known that if a designer does everything right to ensure that a structure does not fail due to yielding, fracture, fatigue, creep or stress-rupture, or impact, most, if not all structures will eventually fail because they corrode or wear away! Corrosion can be the most serious problem and the overriding concern for some design applications, with marine hardware being a prime example. Corrosion can lead to the complete failure of a fastener or a joint, and it can occur by any of several mechanisms, including galvanic corrosion, stress corrosion, fretting corrosion, pitting, or oxidation or rust.

The most common form of all corrosion by far is general oxidation; typified by the rusting of steel structures and fasteners. Corrosion of steel, and many other metals and alloys, occurs becuase the metal is electropositive and tries to lose electrons to achieve a more stable electron configuration and lower energy state. One easy way for a metal to do this is to react with an electronegative element, which is seeking to add electrons to achieve a more stable electron configuration and lower energy state. Hence, metals tend to react chemically with electropositive elements, which include O_2, Cl_2, Br_2, S and some oxides of S, and carbonates (based on CO_3), as the most common examples of corrosive films.

The next most common form of corrosion is galvanic or electrochemical corrosion. Galvanic corrosion occurs when two dissimilar metals (or a metal and graphite, as another common example) are exposed to an electrolyte (which allows movement of electrons and ions back and forth) to form an electrochemical or galvanic cell. This situation leads to the sacrificial loss of the more electropositive or anodic metal in the electrochemical couple. The electrolyte can be something as aggressive as an inorganic acid (e.g., sulfuric or nitric acid formed when oxides of sulfur or nitrogen from

emissions from various combustion processes combine with moisture in the air); something somewhat less aggressive, but still aggressive, like saltwater or saltwater spray in, over, or near the ocean or something seemingly benign like rain, dew, snow, or high humidity. Galvanic corrosion is a distinct possibility with any dissimilar metal assembly or structure and with metals near some electronegative nonmetals like graphite.

Stress corrosion is a particular condition of corrosion where cracks are initiated and propagate in a material or structure under the combined effects of imposed stress and a corrosive environment. Any structure or structural element fabricated from a susceptible metal or alloy and subjected to high stress concentrations (e.g., threaded fasteners) is prone to this type of corrosion attack. Corrosion generally starts at a point of high stress concentration, a crack nucleates, and propagation occurs under continued exposure to the corrosive agent and the stress state, particularly if that stress state is tensile in nature. Eventually, damage can be so severe that catastrophic failure can occur by overload.

Pitting or "concentration-cell" corrosion occurs in some metals when the metal is exposed to certain corrosive agents that act as electrolytes. Corrosion occurs electrochemically in the single-metal or single-alloy species because of the effective localized galvanic cell established between the metal or alloy and an oxygen gradient established in the metal or alloy in the presence of the electrolyte.

Fretting corrosion is more closely related to wear and occurs when two surfaces in contact experience slight, periodic relative rubbing motion. Fretting corrosion differs from wear, however, in that the relative velocity of the two surfaces in contact is much slower than that encountered in other types of wear, and since the two surfaces are never brought out of contact, there is no chance for the corrosion product to be removed, which can exacerbate the problem. Initially, surface pitting and deterioration occur, and then fatigue cracks form and grow.

To prevent galvanic corrosion, fasteners should be selected to be as electrochemically compatible with materials in the joints as possible. To prevent most other forms of corrosion, protective coatings or finishes should be employed. These can include primers, paints, inhibitors, conversion coatings, oils, greases, or platings. Fretting corrosion is particularly difficult to prevent, unless the relative motion can be prevented or the coefficient of friction can be reduced through the use of a lubricant.

Problems analogous to corrosion associated with metal can occur due to environmental degradation of other materials; examples include, but are not limited to, craze cracking of polymers, chemical fatigue of glasses, swelling of thermosetting polymer-matrix composites, embrittlement upon drying or UV exposure of elastomers, leaching of cement and/or concrete by acid rain or contaminated water (e.g., from rusting steel supporting or reinforcing the concrete), etc. Because of the sheer diversity of mechanisms of environmentally induced degradation in porous ceramics (like cement, concrete, and brick), plastics or polymers, wood, and composites of various types, the reader is referred to specific references on these materials given in pertinent chapters in Part 2 of this book.

2.8 INTEGRALLY ATTACHED JOINTS

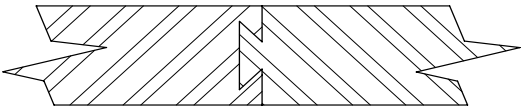
2.8.1 Integrally Attached Joints Defined

When actual geometric features of parts or structural elements themselves can be used to cause interference and interlocking between or among those parts or elements, integrally attached joints and an integrally attached assembly or structure are the result. As mentioned at the start of this chapter (see Subsection 2.2.1), these features can be macroscopic (i.e., have dimensions on the same length scale as dimensions of the parts or structural elements to which they are integral) or microscopic (i.e., have dimensions that are on a much smaller scale than the parts or elements to which they are integral). Macroscopic features can exist naturally in a part of an intended assembly (e.g., a fork in a stick into which another part can interlock, or stones with natural shapes that can interlock), can be designed and fabricated into the geometry of a part (e.g., dovetails and grooves in wood parts of a piece of furniture, or cantilever hooks and catches molded into plastic parts of a hand-held calculator), or can be processed into parts (e.g., crimped metal terminal connectors on wires in an electrical assembly, or punched or "staked" metal bearings in a machine or engine housing). Microscopic features usually occur naturally (e.g., asperities on the surfaces of mating parts, which prevent stacked rectangular bricks from sliding along their mating surfaces) but can be designed and processed in (e.g., knurling on the surface of mating parts like wedge-grips in a tensile testing machine), causing joining through—or, in this case, aided by—friction. A particular advantage of all such integral attachment features is that supplemental parts (e.g., fasteners) are not needed to achieve mechanical joining. Figure 2.22 schematically illustrates some typical integral attachments.

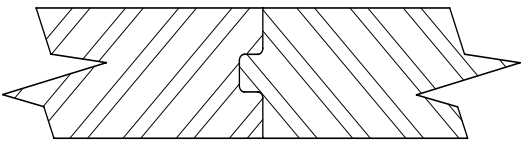
More will be said about these always interesting, seemingly new but actually very old, and seemingly proliferating integral attachment features and methods (see Chapter 3, section 3.5), and much more could be said. (In fact, not only could a book be written about the topic, one should be written!) The intent here is familiarization, not comprehensive education. Toward this goal of familiarization, let's consider three important topics briefly: (1) integral attachment joint and attachment loading, in general; (2) classification of integral attachments, in general; and (3) analysis of snap-fit integral attachment features, in particular.

2.8.2 Integral Attachment Joint and Attachment Loading

The loading imposed on a joint places that joint in simple tension or compression, simple shear, simple bending, simple torsion which develops shear, or more complex combinations of these from different types of simultaneously imposed loads (see Chapter 1, Subsection 1.7.1) or from peculiarities of the joint (e.g., single-overlap shear joints giving rise to bending as well as shear). Hence, the loading imposed on integral attachment joints and the individual attachment features that comprise these joints also fall into one of these categories. In fact, the joints themselves, like fastened



(a)



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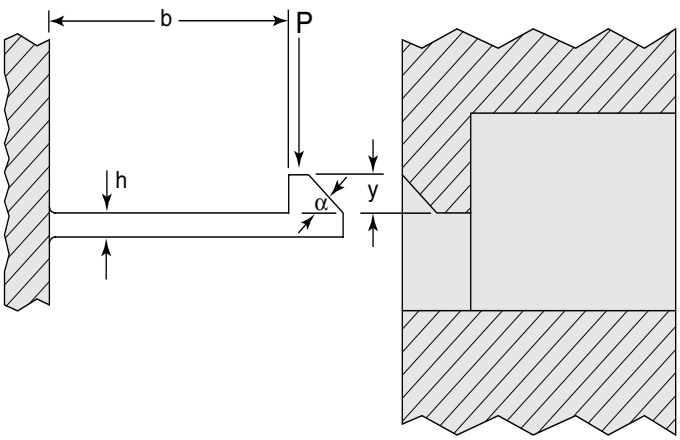

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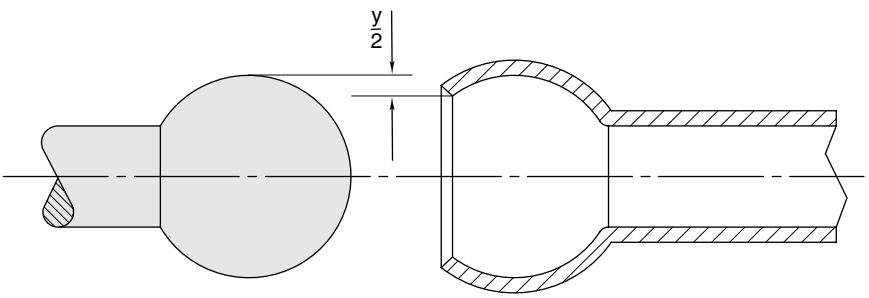

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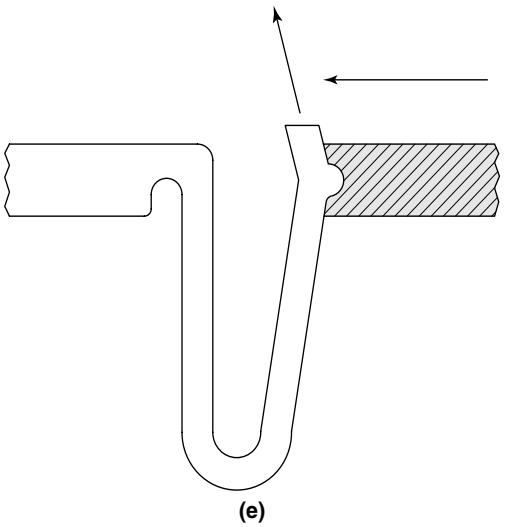

Figure 2.22 Schematic illustration showing some typical integral mechanical attachments, including (a) dovetail joints, (b) tongue-and-groove joints, (c) cantilever hooks and catches, (d) ball-and-socket snaps, and (e) finger snaps.

joints, are of either shear-loaded or tension-loaded types, albeit with no subdivision of shear-loaded joints into the friction type, only into bearing types.

The great variety of integral attachment features (to be presented in Subsection 2.8.3 to follow in this chapter and in Section 3.5 of Chapter 3) expectedly leads to a variety of special problems in the way the attachment feature itself is loaded. So-called "rigid attachment features" (for which "dovetail," "tongue-and-groove," and "mortise-and-tenon" joints, and "Morse tapers" are good examples) are intended to carry loads in either shear only (e.g., tongue-and-groove and mortise-and-tenon joints), tension only (e.g., Morse tapers), or both (e.g., dovetail joints). So-called "elastic attachment joints," for which "snap-fit integral attachments" or "features" and "thermal-shrink fits" are examples, are capable of carrying shear in bearing or friction (which is rare!) or in tension (but with limits). So-called "plastic attachment features" (such as formed-in or processed-in crimps, hems, stakes, or press-fit joints) are able to carry either shear or tension loads, albeit usually in fairly limited or modest in magnitude.

Figure 2.22 shows these various types of integral attachments.

2.8.3 Classification of Integral Attachments by Form and for Design Context

As will be explained in Chapter 6, Welding Processes, it is useful to classify objects or processes to elucidate similarities and differences. When it comes to integral attachments, classification can be based on the form of the attachment or on the design context of the attachment. Classification based on form was hinted at in the previous subsection, where integral attachments have been classified (Messler and Genc, 1998)

as "rigid attachments," "elastic attachments," and "plastic attachments." Rigid attachments are those with a naturally occurring or designed-in, and usually macroscopic, geometric shape that leads to interlocking, interference, and mechanical joining. Loads, whether shear- or tension-type, are carried by these features without any noticeable elastic and no plastic deformation of the feature(s). Joints found in materials that tend to exhibit little elasticity are best designed to be rigid; with dovetail, tongue-and-groove, and mortise-and-tenon joints in wood, and "notched" or "keyed" joints in ceramics, cement, or concrete are good examples.

Elastic attachments are those that accomplish engagement between mating parts, given rise to interference and interlocking, and result in mechanical joining by elastically deforming and recovering with no plastic deformation required or acceptable. Integral attachment joints intended for use in materials that exhibit high degrees of elasticity (but with a reasonable modulus, not as low as so-called "elastomers") are best designed to accomplish joining by elastic deflection and recovery. "Snap-fit" features common in plastic or polymeric materials, as well as "shrink fits" or, occasionally, snap-fits in metals, are generic examples.

Plastic attachments are those that accomplish interference, interlocking, and resulting mechanical joining by actually processing in a locking feature via plastic deformation. Such joints can only be employed with materials that exhibit plastic deformation, yet still retain their strength or mechanical integrity. Ductile metals and thermoplastic polymers are the two examples; formed-in "folded" tabs, crimps, hems, and punched stakes are good examples in metals, and crimps, hems, and punched or heat-set stakes are examples in thermoplastic polymers.

Classification by the form of the integral attachment feature is most useful to process engineers, who are responsible for producing the joints and accomplishing the assembly. For designers, it is generally more useful to classify integral attachment features and joints by their utility based on the shapes of parts to be joined. This form of classification has proven to be more difficult, but several investigators have successfully classified snap-fit attachments in integral attachment, including Bonenberger (1996), Genc, Messler, and Gabriele (1998), Messler and Genc (1998), and Suri and Luscher (2000). While there are subtle differences in the classification schemes suggested by each of these investigators, the overall approaches are the same, that is, decide on the placement or location, number, type (e.g., cantilever hook, compression trap, etc.), and orientation (e.g., in-plane or out-of-plane cantilever hooks) attachment features by considering the "essential" shape of the parts being joined and the loads (i.e., type, direction, and magnitude) to be resisted. Genc et al (1998) and Suri and Luscher (2000) have, in fact, enumerated the theoretical possibilities for all conceivable ways of achieving snap-fit assembly based solely on "essential" geometry of mating parts. In both cases, using a hierarchical approach, most alternatives can be eliminated by answering a few "high-level" questions, and, then, literally every one of a small subset of possibilities (generally, 5 to 10) can be evaluated. The result is a truly optimized integrally attached design.

The interested reader is encouraged to read the pertinent literature on this basis for classification of integral snap-fit attachments (see the cited references section at the end of this chapter).

2.8.4 Analysis of Snap-Fit Integral Attachment Features

Traditional integral attachments, such as the rigid and plastic types, can be analyzed using traditional statics and dynamics. Analysis of elastic snap-fit integral attachments is more difficult to do, and solutions are harder, but not impossible, to find. Essentially, all integral snap-fit features (of which there are many fundamentally different types, as seen in Chapter 3, Subsection 3.5) operate by elastically deflecting during the process of forcing one part to engage with another, elastically recovering to cause locking, and then resisting separation or disassembly through some shape feature. The great advantage of virtually all (if not all) of these snap-fits is that they can be caused to engage with relatively simple single or sequential double motions requiring reasonably low forces well within the elastic range of the material comprising the part and integral snap-fit feature. The essential motions to cause engagement are "push," "slide," "twist" (or "turn"), and "tilt" (Genc et al, 1998), with "pivot" sometimes being countered as a fundamental motion (Bonenberger, 1996), although a pivot actually involves a push followed by a twist, so is not a "fundamental" motion. The combination of a simple motion and a low force to cause insertion make snap-fit assembly simple for automation using robots, for example. The tactile feel and audible sound of a successful engagement, in the form of the "snap" associated with elastic recovery (which gives these integral attachments their name), facilitates insertion control using force or sound feedback.

While insertion force is low, the retention force (i.e., force to cause disassembly) tends to be much higher—often 5 to 50 times higher. The difference between the insertion force and retention force is the direct result of the design of the feature.

Virtually all snap-fit features are analyzed as beams subjected to an elastic deflection with automatic recovery.[16] Figure 2.23 shows how various designs for a so-called "cantilever hook" snap-fit feature can be analyzed as a beam. References are given at the end of this chapter for the analytical, empirical, analytical/experimental, and/or numerical analysis of a variety of snap-fit feature types, including cantilever hooks (Luscher 1996), post-and-dome (Nichols and Luscher, 2000), compression hook (Lewis, Knapp and Gabriele, 1997), bayonet-and-finger (Lewis, Wang and Gabriele, 1997), and annular snaps (Mobay-Miles, now Bayer Polymers, 1990).

In closing, it should be clear that integral attachments, in general, and integral snap-fits, in particular, provide exciting possibilities for mechanical joining in the future.

SUMMARY

One of the most attractive and most popular methods for joining parts into assemblies and structural elements into structures is *mechanical joining*, which involves two major subclasses of *mechanical fastening* and *integral (mechanical) attachment*. In all manifestations, mechanical joining relies solely on mechanical forces to hold

[16] Recovery is critically important so that polymeric part features are not kept under stress, with the risk of stress relaxation weakening the attachment.

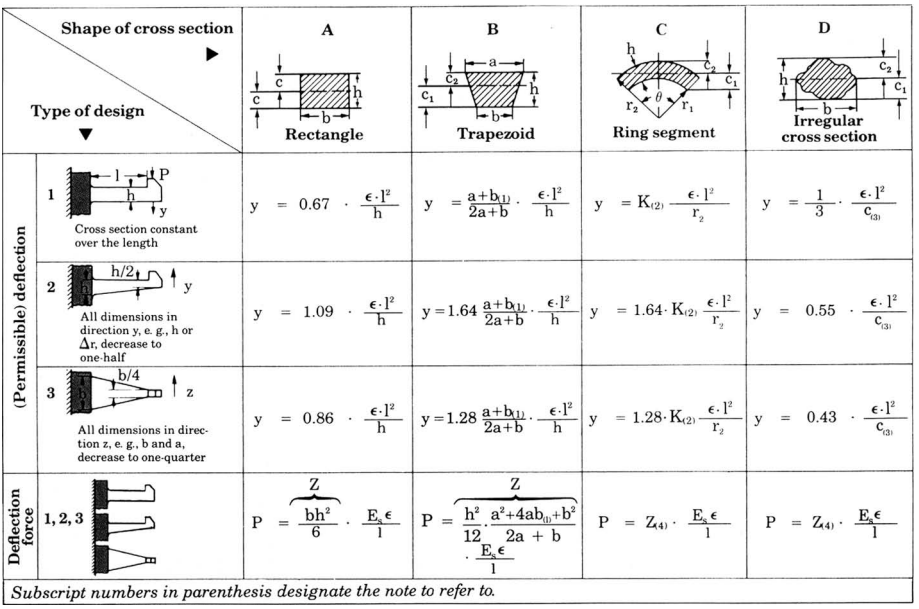
Shape of cross section
Type of design
A
Rectangle
B
Trapezoid
C
Ring segment
D
Irregular cross section
(Permissible) deflection
Deflection force
Cross section constant over the length
All dimensions in direction y, e. g., h or Δr, decrease to one-half
All dimensions in direction z, e. g., b and a, decrease to one-quarter
1, 2, 3
y = 0.67 · ε·l²/h
y = (a+b(1))/(2a+b) · ε·l²/h
y = K(2) ε·l²/r2
y = 1/3 · ε·l²/c(3)
y = 1.09 · ε·l²/h
y = 1.64 (a+b(1))/(2a+b) · ε·l²/h
y = 1.64 · K(2) ε·l²/r2
y = 0.55 · ε·l²/c(3)
y = 0.86 · ε·l²/h
y = 1.28 (a+b(1))/(2a+b) · ε·l²/h
y = 1.28 · K(2) ε·l²/r2
y = 0.43 · ε·l²/c(3)
P = Z · Es ε/l
P = Z/12 · (h²·(a²+4ab(1)+b²)/(2a+b)) · Es ε/l
P = Z(4) · Es ε/l
P = Z(4) · Es ε/l
Subscript numbers in parenthesis designate the note to refer to.

Figure 2.23 Schematic illustrations of various designs for cantilever hook snap-fits along with equations giving their deflection under elastic loading as beams. (Reprinted from *Snap-Fit Joints in Plastic: A Design Manual* by Mobay Plastics and Rubber Division of Miles-Mobay, now Bayer Polymers, Pittsburgh, PA, 1990, with permission.)

structures (versus materials) together. Interlocking and interference of naturally occurring, designed-in, or processed-in geometric features, on a macroscopic and/or microscopic scale, cause joining without the need for chemical reactions or atomic-level bond formation. As a result, mechanical joining uniquely allows parts of an assembly to move relative to one another to provide needed system functionality, while maintaining part arrangement, proximity, and orientation. Further, the process causes no chemical or microstructural changes in the material being joined, so dissimilar types can be combined easily, and all can be intentionally disassembled to allow maintenance, service, repair, upgrade, ultimate disposal, or portability. On the downside, both fasteners and integral attachment features give rise to stress concentration at points of fastening or attachment, which can be problematic with certain viscoelastic, brittle, or high anisotropic materials.

When fasteners are employed, two types of joints are identified, depending on the direction of joining loads in relation to the fastener's axis: *shear-loaded joints* (when loading is at a right angle to the fastener's axis) and *tension loaded* (when loading is parallel to the fastener's axis). Shear-loaded joints are further sub-classified as *bearing* or *friction type*, depending on whether they use the fastener as strictly a "pinning" point against shear or to develop a clamping force to introduce compression to resist tension and/or cause friction between joint elements to resist shear.

For both major types and the two subtypes, the *allowable-stress design procedure* is used to assure that allowable stresses are not exceeded in the fastener (by shear

overload), in the joint elements or plates (by tensile overload), around fastener holes (by bearing-induced plastic deformation of the joint plates), or because fasteners literally tear out at joint plate edges. For friction-type joints, this analysis compares the slip resistance developed by fastener clamping to the loads that would cause these modes of failure. The analysis of tension-loaded joints focuses on the proper use of and determination of joint preloading (or clamping force) compared to the fastener's working load. Methods of achieving target preloads, relating preload to the torque used to install (tighten) clamping-type fasteners (e.g., bolts and machine screws), methods for measuring preload initially and later on in service, and the various mechanisms by which preload can be lost are all important in the performance of a tension-loaded joint. When dynamic cyclic loading is involved, special precautions must be taken to reduce fasteners' or joints' tendency to fail in fatigue. Other factors that can affect the performance of fasteners and fastened joints are bending loads, vibrational loads, and corrosion and wear. Finally, the seemingly new and rapidly growing use of integral attachment features, which are actually quite ancient, are discussed in terms of their special capabilities.

QUESTIONS AND PROBLEMS

1. Define *mechanical joining* in your own words, and differentiate between the two major sub-processes.
2. What two related functions are made possible uniquely by mechanical joining among all joining methods? What other major advantages does mechanical joining offer relative to its effects on the materials it is used to join? How do these latter features compare to adhesive bonding, to welding, to brazing, and to soldering?
3. Give a couple of reasons why and examples where mechanical joining can be used to favorably affect a product's or structure's aesthetics.
4. Give a couple of advantages that *mechanical fastening* has over *integral mechanical attachment*. Give a couple of advantages *integral mechanical attachment* has over *mechanical fastening*.
5. Describe what you think is involved in automating mechanical fastening for certain types of fasteners, including nails, self-tapping (e.g., wood) screws, nuts and bolts, upsetting rivets, staples, and stitches. State whether you know of an example of the automation of each, and, if you do, state what form that automation takes.
6. What is the single biggest potential shortcoming of mechanical fastening as a joining method? Explain your answer. Does integral mechanical attachment pose the same problem? If so, when? If not, under what circumstances?
7. While suited to the joining of all materials, explain why mechanical fastening is either easy or difficult for each of the following:
   - metals
   - ceramics
   - glasses

- plastics or polymers
- composites (in general)

8. Distinguish between shear- and tension-loaded fastened joints. Distinguish between the two sub-types of shear-loaded joints. Give your own examples (two each) for the following:
   - shear-loaded bearing-type
   - shear-loaded friction-type
   - tension-loaded
9. Calculate the net area for the staggered 3-row pattern of ½"-diameter rivet holes in the joint element shown in Figure P2.9 below. Do not forget to use the hole tolerance factor.

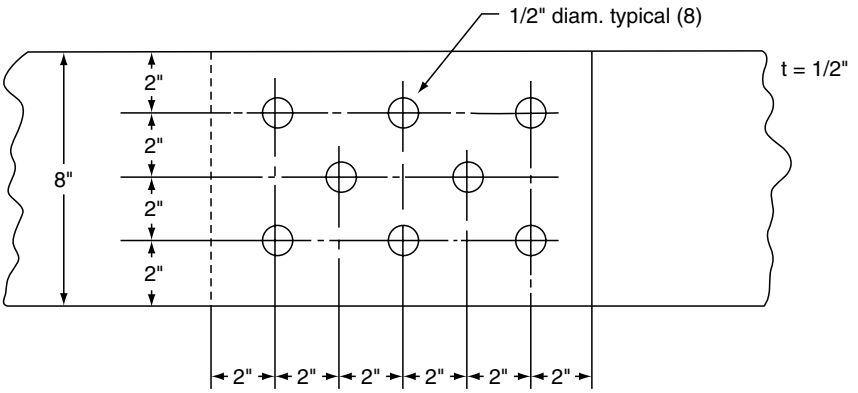

Figure P2.9

10. If the joint in Problem #9 were composed of ASTM A36 steel, for which the yield strength is 36 ksi and the ultimate strength is 58 ksi, what would be the maximum tensile load (in lbs. force) that could be imposed under the AISC specification? Hint: see the reference to the AISC specification in Section 2.4.4.
11. Apply the *allowable-stress design procedure* to the single-overlap, bearing-type shear-loaded joint shown in Figure P2.11. Assume the bolts in the joint are made from ASTM 325 steel and have 14 threads per inch and that the joint plate is made from ASTM A36 steel. Hint: look at the bolt in Figure P2.11 carefully!

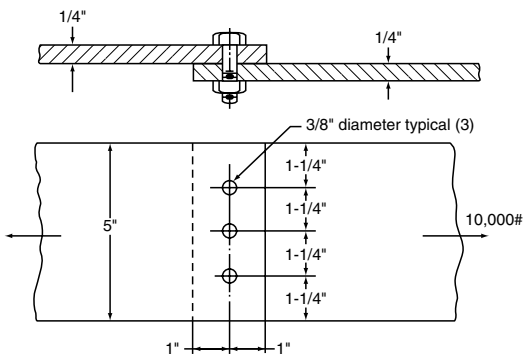

Figure P2.11

12. Suppose the bolts in Problem #11 were threaded for their entire length, from just under the head to the end of the shank. How would the values for each stress in the *allowable-stress design procedure* change? Calculate each new stress value.
13. What would the edge distance (i.e., the distance from the center of the bolt hole to the edge of the joint plate) be if tear-out were just possible for the joint shown in Figure P2.11?
14. For the joint shown in Figure P2.11, what would be the maximum load that could be applied to just cause the joint to fail? Hint: check each possible failure mode for the allowables for the bolt and joint plate materials.
15. Apply the *allowable-stress design procedure* to the double-overlap, bearing-type shear-loaded splice joint shown in Figure P2.15. Assume the same bolt and joint plate materials as in Problem #11. Assume the bolts have a pitch of 2.0 mm.

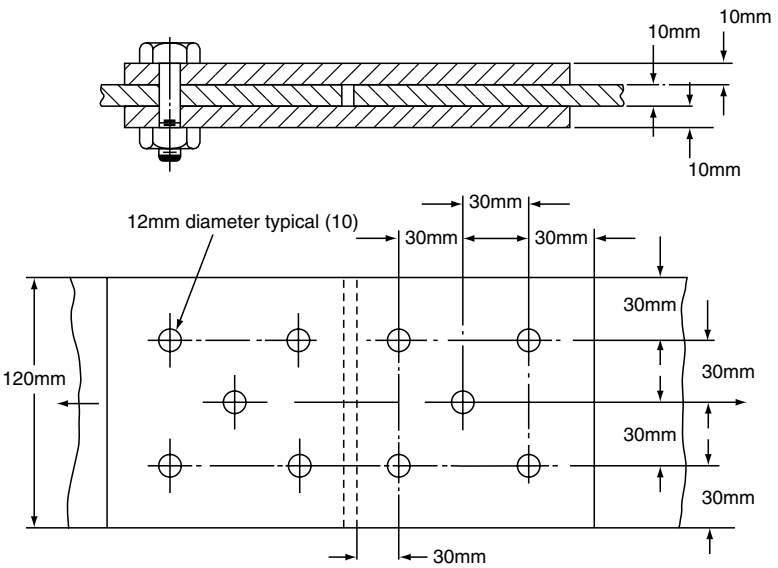

Figure P2.15

16. For the joint shown in Figure P2.15, what would be the maximum load that could be applied to the joint to just cause failure? Hint: check each failure mode.
17. Using the *allowable-stress design procedure* for the joint shown in Figure P2.15, what value of target preload would be needed to just assure there would be no slip at the joint interface, assuming the joint elements were treated to have a slip coefficient (of friction), μ_s, of 0.40?
18. For the joint shown in Figure P2.18, what is the force on each rivet in the pattern in terms of the general load P and dimensions shown (i.e., L, x_1, x_2, and w)?
19. Suppose the load on the joint shown in Figure P2.18 were 300 kN, and the dimensions were $x_1 = 40\,\text{mm}$, $x_2 = 80\,\text{mm}$, $L = 320\,\text{mm}$, and $w = 80\,\text{mm}$. What would the load be on the most highly loaded fastener(s) if the fasteners were each 10 mm in diameter?

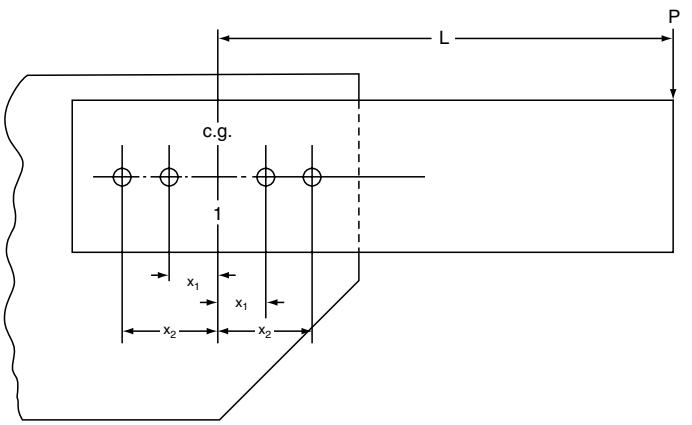

Figure P2.18

20. For a joint like that shown in Figure P2.20, what is the load in the most highly loaded fastener(s) for the 30,000 lbs. force load shown?

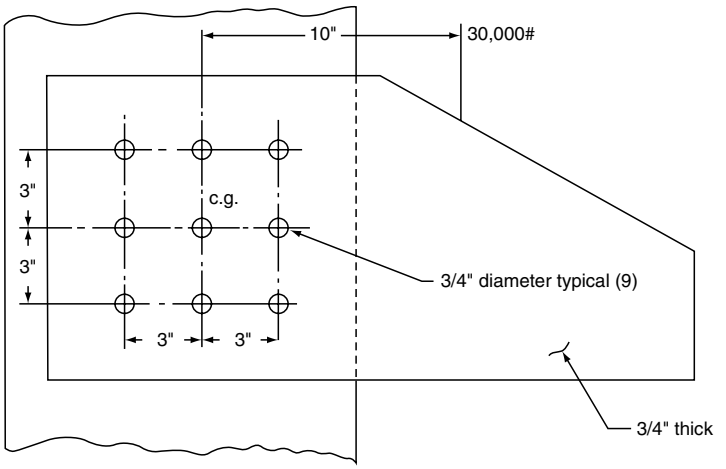

Figure P2.20

21. For a joint like that shown in Figure P2.20, if the fasteners were ASTM A490 steel bolts, what would be the maximum allowable load? Hint: use allowables for A490 steel in shear and bearing, and ignore threads.
22. Describe the general procedure for determining a target preload for a tension-loaded joint, giving the rationale for this procedure.
23. Why is the torque used to tighten a bolt not a good measure of the level of preload attained? How can preload be measured fairly accurately during fastener installation? How can the preload remaining in a fastener be measured in service without disrupting the structure?
24. Describe the four sources of loss of preload for a non-gasketed joint. Differentiate between short-term and long-term sources.

25. What are the expected effects of each of the following situations on each of the four sources of loss of preload you identified in Problem #25?
    - A joint made from formed sheet metal parts
    - A joint made from precision molded thermoplastic
    - A joint made from precision ground alumina ceramic
26. Why is fatigue such an insidious potential mode of failure for mechanically fastened structures? How might one conduct maintenance to preclude catastrophic failure by fatigue of fastened joints?
27. What are several things to watch out for in mechanically fastened joint design if the structure is fatigue critical? Differentiate between things to watch out for in the fasteners, the way they are installed, and the way the joint elements are arranged.
28. In what ways does unanticipated bending cause problems with joints designed to operate as follows?
    - Shear-loaded bearing-type joints
    - Shear-loaded friction-type joints
    - Tension-loaded joints
29. How do vibrations cause loosening of a bolted joint? What types of things can be done to prevent loosening under vibrational loads?
30. Describe the difference between various mechanisms of corrosion that can occur in mechanically fastened metal joints. Explain what mechanism would be most likely to occur for each of the following, and why:
    - Austenitic stainless steel rivets in Monel joints operating in sea water
    - Bolted tension joints in a 70Cu–30Zn yellow brass used in an ammonia environment

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Chapter 3

Mechanical Fasteners, Integral Attachments, and Other Mechanical Joining Methods

3.1 INTRODUCTION

Mechanical joining of parts or structural elements into assemblies or structures requires some means for developing interference forces or interlocking between those parts or elements at their mating or faying surfaces to prevent unwanted movement (at least in some directions) or unintentional disassembly. This can be done on a macroscopic or microscopic scale relative to the dimensions of the parts or structural elements themselves, and totally without the need or preference for any atomic-level bonding from either chemical interaction or reaction or electromagnetic interaction forces. The interference forces may need to resist joint separation in shear or tension or both, depending on the direction of the externally applied or internally generated loads relative to the joint. Shear forces act to cause the joint to slide or rotate parallel to the joint interface without separating, and tension forces act to cause the joint to separate by being pulled or pushed open normal to the joint interface. Obviously, sliding or rotation of one joint element relative to another can occur without necessitating that the joint parts or elements cause the assembly or structure to come apart (i.e., disassemble). Such uniquely allowed[1] relative motion in one or more degrees of freedom[2] enables dynamic assemblies or structures to perform functions requiring motion between or among their parts or components. Furthermore, the joint may resist either sliding or rotation (and eventual separation) in shear or separation in tension by some pinning action in

[1] What is meant by "uniquely allowed" is that *only* mechanical joining methods permit intentional relative motion between parts of an assembly or structure to perform some function or set of functions (see Subsection 2.2.2, "Advantages and Disadvantages of Mechanical Joining").

[2] "Degrees of freedom" refer to the six directions of motion possible in a three-dimensional (i.e., real) assembly or structure, three of which are in the three orthogonal directions of a Cartesian coordinate system (allowing translation(s) parallel to one or more of the Cartesian axes), and three of which are around these three Cartesian coordinate axes (allowing rotation(s) around one or more of the Cartesian axes). When relative motion is needed for functionality, one or more of these degrees of freedom must be left unconstrained, while all the others must be constrained to hold the assembly or structure together. Whenever any degree of freedom is allowed in translation, some means must be provided to prevent eventual separation if the motion is not limited.

shear using bearing forces or clamping action using tension forces, or shear movement (and eventual separation) by friction arising from a clamping force.[3]

When the required interference force(s) and resulting interlocking is (are) provided by a supplemental device or structural entity that is separate from the parts or structural elements being joined, *mechanical fastening* (using a *mechanical fastener* or *fasteners*) is said to be involved. When the interference force(s) and resulting interlocking is (are) provided by some natural, designed-in, or processed-in geometric feature of the parts or elements themselves, *integral mechanical attachments* are said to be involved. While these are the only two possibilities, there are some manifestations of one or the other that may not be readily recognizable (e.g., knots with ropes, couplings, clutches, etc.).

Figure 3.1 shows a large bolted steel truss structure, while Figure 3.2 shows a house being "framed out" using nailing to join framing lumber, both of which involve mechanical fastening. Figure 3.3 shows a modern consumer product held together by designed-in integral snap-fit attachment features.

This chapter considers the various types of mechanical fasteners and mechanical fastening and integral (mechanical) attachment methods, readily recognizable and not.

Figure 3.1 A large steel truss bridge constructed from pre-fabricated detail parts, subassemblies, and modules using bolting. (Courtesy of the Williams Bridge Company, Manassas, VA, with permission.)

[3] These different approaches apply to the bearing type and friction type of shear-loaded joints and to the tension-loaded joints described in detail in Chapter 2, Sections 2.4 and 2.5.

(a)

(b)

Figure 3.2 Construction of wood-frame houses and other small buildings typically involves nailing of the lumber or engineered wood products; here using manual nailing (a) and power nailing (b). (Courtesy of the APA–The Engineered Wood Association, Tacoma, WA, with permission.)

Figure 3.3 Many modern consumer products, here the caster of a modern office chair (see Figure 15.10a), are held together by designed-in elastic snap-fit integral attachment features. This caster has a molded-in receiver that accepts and locks onto the recessed groove on a molded-in metal pin in the chair leg. (Courtesy of Steelcase, Inc., Grand Rapids, MI, with permission.)

Fasteners are divided into two broad, important, and fundamentally different categories: (1) those that use threads to develop the needed interference forces, usually through clamping (i.e., threaded fasteners); and (2) those that develop the needed interference principally by a pinning action without any need for threads (i.e., unthreaded fasteners). Methods that accomplish mechanical joining without fasteners and rely on interlocking to obtain the needed interference are subdivided into: (a) those that rely on integral features that are designed into the joint elements; (b) those that rely on elastic interaction with no obvious designed-in features; and (c) those that rely on features that are plastically processed into the joint elements to effect joining. Finally, some novel but important means of mechanical joining that are difficult to recognize as involving a fastener are described.

3.2 FASTENERS VERSUS INTEGRAL ATTACHMENTS OR INTERLOCKS

3.2.1 The Role of Interlocking in Mechanical Joining

In mechanical joining, the forces needed to keep the parts or elements making up the joint in proper juxtaposition (i.e., relative order or arrangement, proximity or direct contact, and relative orientation), which enable the carrying and transfer of loads throughout the structural entity to achieve required function, arise from strictly mechanical versus chemical or physical/electromagnetic means. Whether such joining employs fasteners or integral mechanical attachment features, macroscopic forces usually arise from macroscopic devices (e.g., fasteners) or naturally occurring, designed-in, or processed-in macroscopic geometric features. These cause the different parts or structural elements to nest or mate together, to interlock (in not less than one, but as many as six degrees of freedom!), and to interfere on a macroscopic scale (i.e., on a scale comparable to the dimensions of the parts or elements themselves). On the other hand, microscopic features that are naturally occurring or are designed and processed in also contribute to mechanical joining by creating interlocking on a microscopic scale relative to the dimensions of the parts or elements comprising the assembly. The most common—and, in fact, ever-present—naturally occurring features are the ''peaks and valleys'' (i.e., asperities) that are always present on the surfaces of real materials and parts. While very small relative to the size of the joint elements or fasteners on which they appear, these asperities can give rise to very large forces in the form of friction.[4] This is because so many interferences are created, each giving rise to a small force but in total giving rise to a very large force. Obviously, microscopic interlocking always contributes to mechanical joining, regardless of whether fasteners or integral attachment features are employed or the size of these fasteners or features.

[4] The force arising from friction is given by the product of the normal force acting to squeeze parts together times the coefficient of friction (which is a complex function of the size, number, and type of interactions among asperities on mating parts) and the area over which the friction acts. Hence, the force of friction increases as the normal (or clamping) force is increased and as the area over which mating contact occurs increases, for any particular coefficient of friction.

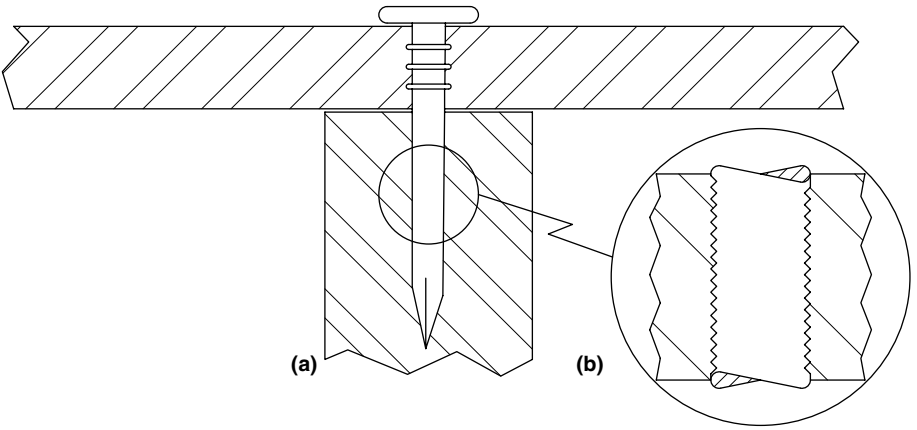


Figure 3.4 Schematic illustration of mechanical interlocking on both a macroscopic (a) and microscopic (b) scale, exemplified by a nail in wood.

Figure 3.4 schematically illustrates mechanical interlocking on both macroscopic and microscopic scales.

3.2.2 Mechanical Fasteners

Mechanical fasteners are supplemental mechanical devices that are used to create macroscopic interlocking between or among abutting or mating joint elements, with the so-called "fastener" interfering with each joint element to transfer load from one element to the other either in shear or in tension. Since the forces involved are purely mechanical, it is possible for fasteners to allow relative motion between the parts or between the parts and the fasteners, although this is rare and usually incidental! Their purpose is to keep parts or structural elements in proper arrangement, proximity, and orientation to allow the overall assembly or structure to perform its function(s) without unwanted separation or, in the extreme, disassembly. Certain types of fasteners, because of both their inherent design geometry and the way in which they are capable of applying forces to the joint elements (or vice versa), are intended to function in shear, using a bearing force between the fastener and each joint element to transfer loads between or among elements. Other types are intended to function in tension, using a clamping force or preload to the joint elements to transfer loads between or among elements. *Tension-type fasteners* are intended to prevent any separation of the joint elements and, because of the clamping force they are required to apply to function properly, will not allow motion of any kind between the joint elements. *Shear-type fasteners* are capable of holding joint elements together in some directions to prevent unwanted separation, but they still allow relative motion in some other direction(s) or degrees of freedom. Tension-type fasteners carry loads

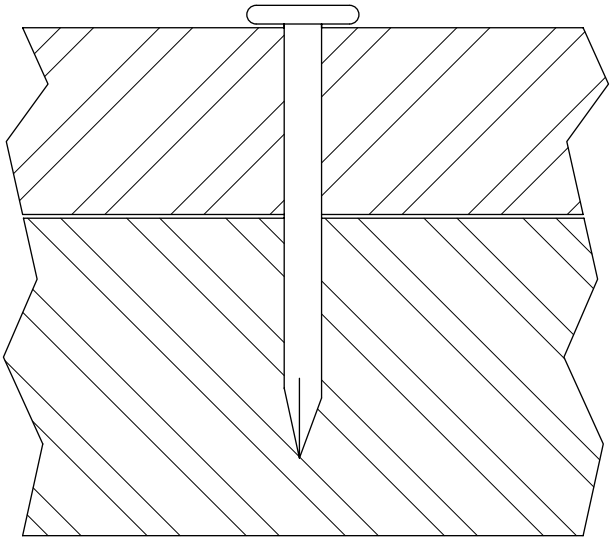
parallel to their axes, while shear type fasteners carry loads perpendicular to their axes.

The type of load a mechanical fastener is intended to tolerate and resist drives the design geometry of the fastener, its method of installation and, to a lesser degree, its material of construction. For *bearing-type shear-loaded joints,* the fasteners must be able to apply and tolerate a high-pressure force on the joint elements, known as a "bearing force." Shear strength combined with shear stiffness are key properties of the fastener material, while high bearing strength is the key property of the joint element(s). Fastener shape or geometry and method of installation tend to be quite diverse, with rivets, pins, keys/keyways, nails, self-tapping screws, staples, and stitches being examples of such fasteners.

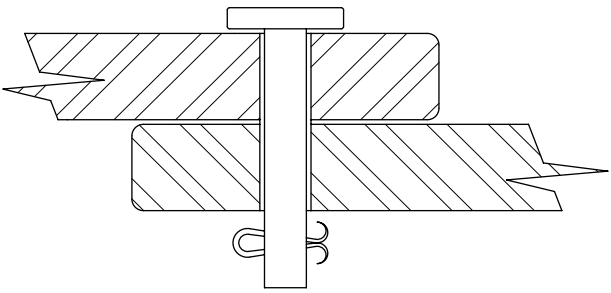
For *friction-type shear-loaded joints* as well as *tension-loaded joints,* the fasteners must be able to apply a compressive or clamping force to the joint elements. This force must be of sufficient magnitude that the resulting friction force (from the clamping force times the coefficient of friction of the joint elements) prevents any slip between the elements in friction type shear-loaded joints (see Subsection 2.4.1). For tension-loaded joints, the magnitude of the clamping force must be high enough to develop reasonable compressive stress in the joint elements to offset service tensile stresses imposed on the joint. Tensile strength combined with stiffness are key properties of the fastener material, while compressive strength and, especially, stiffness of the joint element "stackup" that is higher than for the fastener are key properties of the joint elements of tension-loaded joints. Obviously a high coefficient of friction at the mating surface between joint elements is also a real asset for friction type shear-loaded joints (as will be seen later in this chapter). Fastener shape is almost always a "headed" and "footed" right cylinder. The method of installation is absolutely critical, with hot upsetting, axial shrinkage, and tightening of oppositely-threaded fastener and joint elements or mating fasteners predominating. The only reliable fasteners for either of these joint loading situations are bolts and their smaller cousins, machine screws with nuts; most self-tapping screws (which make their own hole and mating threads as they are installed), or operating with internally threaded joint elements. Hot-set rivets and some two-piece rivets are also used, albeit incorrectly.

Given these requirements, *mechanical fasteners* are broadly classified into two types: (1) those that are designed primarily to develop clamping forces or preload through the use of threads, called *threaded fasteners* and (2) those that are designed primarily to resist shear through bearing with a pinning action, called *unthreaded fasteners*. (In fact, threaded fasteners can also be used to resist shear through bearing with a pinning action.) Threaded fasteners facilitate intentional disassembly, which is one—if not the only—major advantage of mechanical joining in general, and mechanical fastening, in particular. Some unthreaded fasteners, such as pins, keys, and nails, are easy to remove, while others, such as upset rivets and various shrink-fits, take some effort to remove.

Figure 3.5 schematically illustrates some general mechanical fastening methods and fasteners.



(a)



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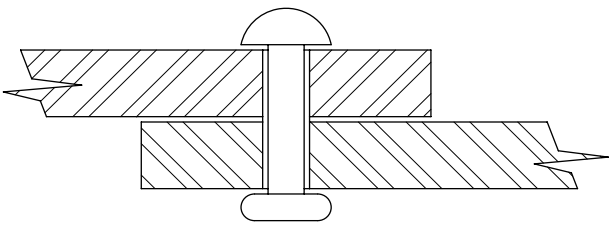

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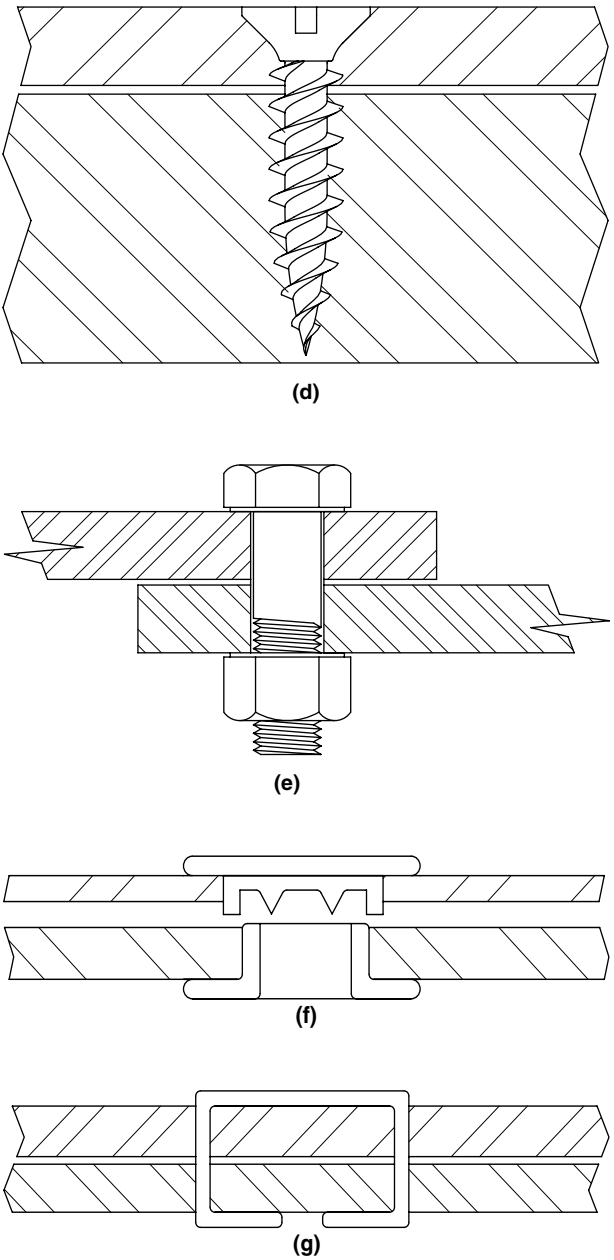


Figure 3.5 Schematic illustration of some general mechanical fastening methods and fasteners, including: (a) a nail in wood; (b) a pin (with locking Cotter pin) in metal; (c) an upset rivet in metal; (d) a self-tapping screw in wood; (d) a nut and bolt in metal; (e) mating eyelets/grommets in a soft material, such as fabric or leather; and (f) a staple in paper, cardboard or leather.

3.2.3 Integral Attachments or Interlocks

The second major category of mechanical joining besides mechanical fastening is *integral mechanical attachment* or simply integral attachment or interlocking. Unlike fasteners (which are special supplemental parts needed to create an assembly or structure from detail parts or structural elements), integral attachments are geometric features that are physical portions of the parts or structural elements comprising an assembly or structure. These features may occur naturally in the part or structural element as part of its natural geometry (e.g., a fork in a stick or naturally meshing shapes of two particular stones). Alternatively, they may be designed into parts or structural elements as a detail to accomplish joining of those parts or elements with these fabricated-in details (e.g., tongues-and-grooves machined into strips or planks of wood, or various catches and latches molded into thermoplastic parts). They could also be processed into the parts or structural elements as they are actually being assembled (e.g., soft metal terminal connectors crimped onto copper wires, or bronze bearings punch-staked into cast-iron machine housings). In each and every case, however, these features (as opposed to supplemental fasteners): (1) are integral (not supplemental) to the parts or structural elements; (2) do not add to the part count of the assembly (to further complicate and add to the labor intensity of assembly); (3) are usually explicitly selected (if naturally occurring) or designed to facilitate assembly with lower forces and simpler motions than for fasteners; (4) facilitate the automated assembly of parts by being ever present with the parts and requiring simple motions for their insertion/engagement or removal/disengagement; and (5) add little or nothing to the weight of the parts (compared to many fasteners).

Like fasteners, integral attachments may be selected from the wide variety that are generically available (e.g., rigid interlocks like dovetails or mortise-and-tenons, and elastic snap-fit features) or specially designed to handle the type of loading expected for the joint. There are integral features especially able to tolerate and resist shear loads that attempt to cause translation between joint elements (e.g., tongue-and-groove joints in wood and virtually all integral snap-fit features in polymers). Some others are especially suited to tolerate and resist shear loads that tend to cause rotation between joint elements (e.g., punched stakes and integral tabs or keys in metal or plastic parts). And there are some especially suited to tolerate and resist tension loads that tend to cause separation of joint elements or opening of joints (e.g., dovetails-and-grooves in wood, and crimps in metal connectors). Fortunately, there are some that resist both types of loads well.

Most integral attachments can be removed. Rigid types (e.g., dovetails) and elastic types (e.g., snap-fits) are easy to remove and plastic types (e.g., crimps, hems, and stakes) are difficult or very difficult to remove.

Figure 3.6 schematically illustrates several important and representative integral attachment methods and features. Table 3.1 lists various mechanical fastening methods and fasteners, integral attachment methods and features, and other mechanical joining methods.

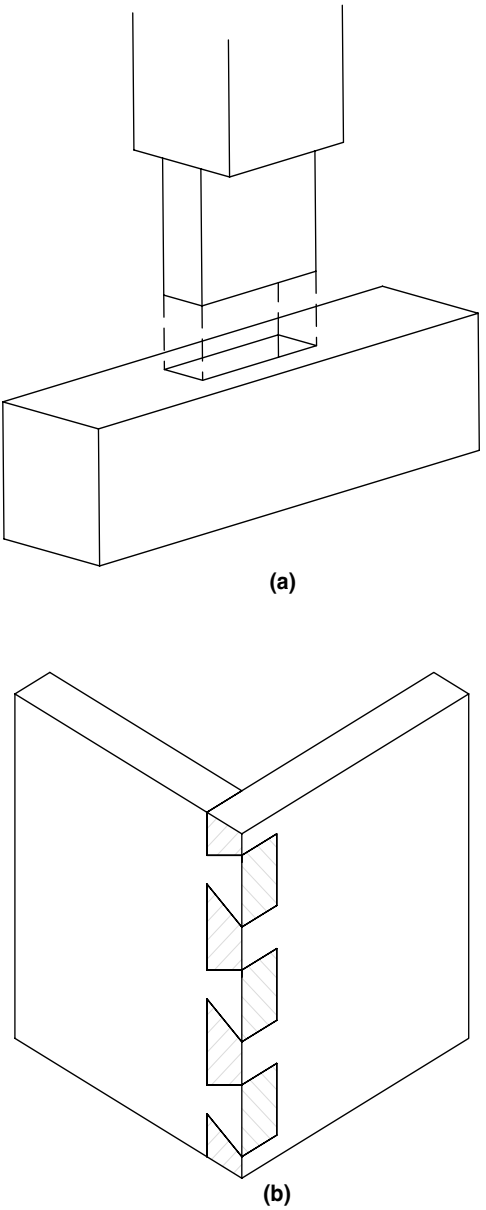
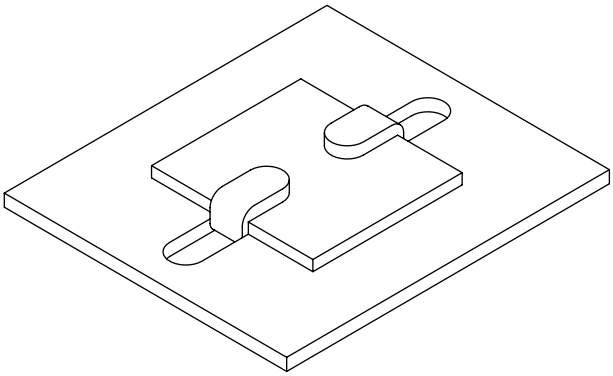
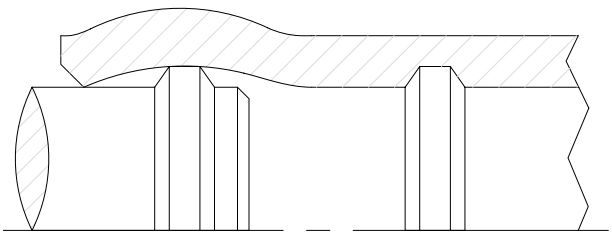


Figure 3.6 Schematic illustration of several important and representative integral attachment methods and features, including (a) a mortise-and-tenon; (b) dovetail-and-groove joints in wood;

(*Continues*)



(c)



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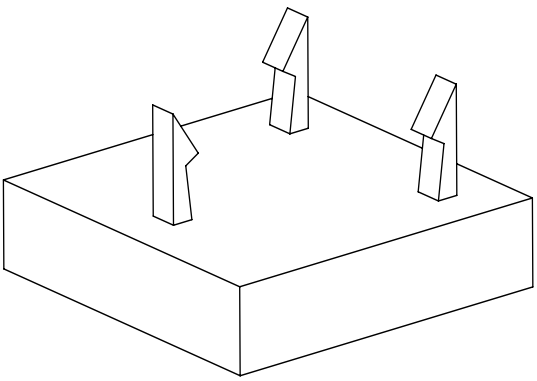

(e)

Figure 3.6 (*cont'd*) (c) formed/folded tabs in sheet metal; (d) annular snap; and (e) cantilever hooks molded into plastic.

Table 3.1 Various Mechanical Fastening Methods and Fasteners, Integral Attachment Methods and Features, and Other Mechanical Joining Methods

Mechanical Fastening
Threaded Fasteners
- Bolts and threaded studs
- Screws or "machine screws"
- Nuts and lock nuts
- Tapping or self-tapping screws
- Sems (integral screw/washer assemblies)

Unthreaded Fasteners
- Upset (one-piece) rivets
- Self-setting or self-upsetting (one-piece) rivets
- Swagged (two-piece) rivets
- Blind or "pop" (multi-piece) rivets
- Nails, brads, tacks, and pegs
- Pins
- Washers and lock-washers
- Eyelets and grommets
- Retaining rings and clips
- Keys and keyways
- Self-clinching fasteners (usually acting as threaded nuts)

Other Fasteners
- Staples
- Stitches and sutures
- Laces, lashings, knots and splices, wraps
- Hook-and-loop (recloseable) fasteners
- Snap-fit fasteners
- Magnetic fasteners and connections
- Couplings
- Clutches

Integral Mechanical Attachments
Rigid Integral Interlocks
- Dovetails-and-grooves
- Tongues-and-grooves
- Dados
- Mortise-and-tenons
- T-slots and Ts
- Wedges or Morse tapers
- Shoulders
- Bosses and posts
- Integral (coarse) threads (e.g., on glass jars)

(*Continues*)

Table 3.1 (*Cont'd*)

Elastic Integral Interlocks
- Snap-fit features
- Thermal shrink fits
- Interference press fits (to cause elastic strain only)
Plastic Integral Interlocks
- Crimps (by crimping)
- Hems (by hemming or "ironing")
- Stakes (by staking)
- Press fits (to cause plastic strain)
- Stitch folding
- "Button-formed" attachments (e.g., Tog-L-Locs)

3.3 THREADED FASTENERS

3.3.1 General Description of Threaded Fasteners

One large and very important category of mechanical fasteners uses threads to achieve their function. These are called *threaded fasteners*. Threads are a helical ramp around a cylindrical shaft or shank that enables the development of a clamping force between the fastener and a joint element or multiple joint elements through the principle of a screw. Rotation of the threaded fastener results in a translation parallel to the axis of the fastener. This translation gives rise to a clamping force from the interaction between the elastic force introduced into the fastener's shank as the spacing between the "head" and "foot" of the fastener is reduced by tightening and compression of the joint elements.

Some threaded fasteners develop this clamping force in a joint by themselves, simply through the microscopic friction and macroscopic locking between the external (or "male") thread on the fastener and the internal (or "female") thread created in one or more joint elements into which this fastener is threaded (creating its path as it goes). Others develop this clamping force through the opposing motion of another, previously internally threaded part. This might be an internally threaded joint element (at least in the most distant or "back-side" element), or a special internally threaded back-side fastener known as a *nut*. In either case, the essential clamping force arises from the opposing translation of the joint element or nut (as the "foot" of the assembly) and the fastener's head. This action is schematically illustrated in Figure 3.7.

Threaded fasteners are essential for use in tension-loaded joints, where development of a clamping force or preload is critical to the proper operation of the joint (see Chapter 2, Subsection 2.4.1 and Section 2.5). They are also essential to friction-type shear-loaded joints, where clamping force is the source of friction needed to resist slip between joint elements (Subsection 2.4.1). This particular capability surely does not

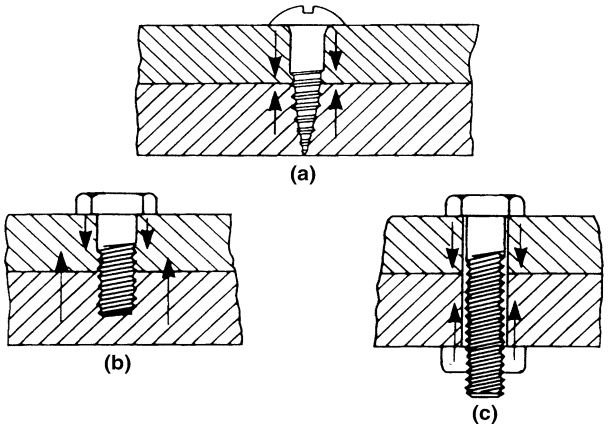

Figure 3.7 Schematic illustration showing how a threaded fastener, such as a self-tapping screw (a), a machine screw into a threaded hole (b), and bolt with a nut (c), develops a joint clamping force. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.2, page 67, with permission of Elsevier Science, Burlington, MA.)

preclude the use of threaded fasteners for bearing-type shear-loaded joints. The four major types of threaded fasteners are (1) bolts; (2) screws (most familiarly, machine screws); (3) nuts (for use with bolts or screws); and (4) self-tapping screws. Besides these major types, there are some special types of threaded fasteners known as "integral threaded fasteners" (including sems, nut-plates, and others) and "self-clinching fasteners." There are also some threaded integral attachments (e.g., "integral threaded studs" and "threaded bodies") that will be described later in Section 3.5.

3.3.2 Threads

The threads on or in threaded fasteners and on or in threaded parts are of two major types, based on the units of dimensions for these threads[5]: (1) Unified Inch Series (or UN or UNJ profile)[6] using English dimensions and (2) Metric Series (or M or MJ profile[7]) using metric dimensions. Figure 3.8 schematically illustrates the basic profile of threads for both types. These threads can be external (i.e., on the shaft of the fastener or on the outside of a threaded cylindrical part) or internal (i.e., in the body of a nut or in a hole in a joint part). External threads carry a secondary "A" in their designation

[5] Actually, there are some other threads known as power-transmitting threads that are used on heavy-duty parts for causing motion using a rotating screw. Examples include a screw jack and screw-type testing machines or drives on machine tools. These types of threads will not be described here, as they are not used for joining. Information can be found in any good machine design reference book or mechanical engineering handbook.

[6] The UNR profile has a rounded fillet at the root of the external thread.

[7] The special MJ profile has a rounded fillet at the root of the external thread and a larger diameter of both the internal and external threads for use under high-fatigue loading (e.g., aerospace applications).

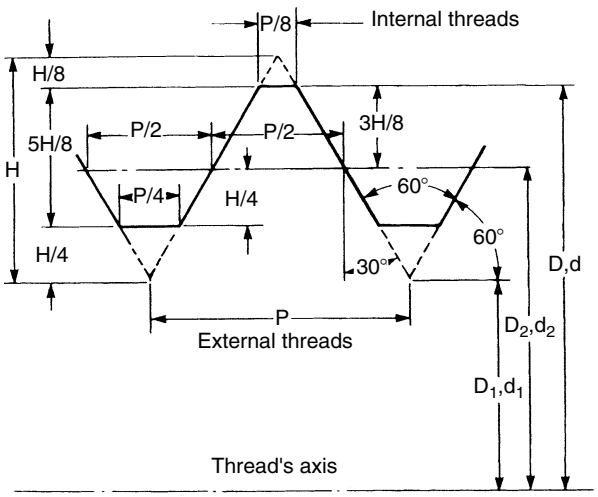

Figure 3.8 Schematic of the basic profile of threads used on bolts and screws for both the Unified Inch and Metric Series. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.3, page 67, with permission of Elsevier Science, Burlington, MA.)

(i.e., UNA, UNRA, MA, or MJA), while internal threads carry a secondary "B" designation (i.e., UNB, UNRB, MB, or MJB) depending on the series and subseries to which they belong. Within each series the actual shape of the crown or root of the thread can differ, having either rounded (U-shaped) or sharp (V-shaped) profiles. The method of fastener fabrication (particularly thread fabrication) has a major influence on thread shape, although the shape is defined in the thread's design.

There are (unfortunately!) several standards that provide complete information on the threads of threaded fasteners such as bolts and screws. The most popular for Unified Inch Series threads is the American National Standards Institute (ANSI) B1.1 specification. Others exist for Metric Series threads under the International Standards Organization (ISO). A more complete list of standards is contained in Table 3.2.

Not surprisingly, the most important parameter for a threaded fastener is the "pitch" of the threads. The pitch refers to the rate of axial advance or translation of the fastener per full rotation or turn, and is almost always constant. A constant-pitch Unified Inch Series consisting of 4, 6, 8, 12, 16, 20, 28, and 32 threads per inch has been standardized, but others are common (e.g., 14 and 40). For the Metric Series the pitch is specified by the actual axial translation produced by one rotation of the fastener (e.g., 2-mm pitch), not by the number of threads per unit of threaded shank length.

While threads are primarily designated by their series, nominal diameter, and pitch, they can also vary in their *coarseness* or *fineness*. This affects the looseness or, contrarily, tightness of fit (which equates to "mechanical slop" between a nut and bolt or bolt or machine screw and internally threaded part). There are three categories of thread fit, as follows: (1) UNC (or MC or MJC) coarse, which offers the most resistance to thread damage by stripping from over-tightening or overload and is best for

Table 3.2 Specifications for Threads Used on Fasteners from Various Standards Organizations

Type Specification	*Source*
AAR Specifications	Association of American Railroads
AMS (or SAE) Specifications	Society of Automotive Engineers
ANSI Specifications	American National Standards Institute
API Specifications	American Petroleum Institute
ASTM Specifications	American Society for Testing Materials
EEI Specifications	Edison Electrical Institute
Federal Specifications	Naval Publication and Forms Center
Handbook H28, National Specifications	National Institute of Standards and Technology (NIST)
IFI Specifications	Industrial Fastener Institute
IOS (International Organization for Standardization) Recommendations	American National Standards Institute
Military Specifications (Mil Specs)	Naval Publications and Forms Center
NAS (National Aerospace Standards Committee) Specifications	National Standards Association

Adapted from Robert O. Parmley, *Standard Handbook of Fastening and Joining,* 2nd ed. New York, McGraw-Hill, 1989, with permission.

aluminum, brass, other low-strength materials, and cast iron; (2) UNF (or MF or MJF) fine, which offers the best vibration resistance; and (3) UNEF (or MEF or MJEF) extra fine, which offers the best performance in thin nuts or internally threaded joint elements and enables fine adjustment of position. Finer threads, by virtue of their finer pitch and smaller thread depth, produce a loading area that is greater than the area for a coarser threaded fastener. The net effect is that the fine-threaded series is typically stronger than the coarse-threaded series and, naturally, allows more accurate adjustment of preload and position. Fine threads are also actually easier to tap into hard materials than coarse threads, while coarse threads, because of their additional clearance, provide latitude for plating or other finishes and are less plagued by the presence of contaminants or burrs during assembly. Figure 3.9 schematically compares threads with different coarsenesses.

Regardless of a thread's coarseness or fineness, there are tolerances on the thread fabrication and, thus, fit during assembly. These are fixed by what is known as the "class" of the thread, where (1) Class 1 provides for a loose fit and affords easy assembly or disassembly; (2) Class 2 provides for a general fit; and (3) Class 3 provides for a tight fit and affords accuracy.

A typical designation (or "call-out") for a threaded fastener (e.g., a bolt) includes the series, nominal diameter, category, pitch, and fit class, with an additional call-out on overall length. An example for each series is:

$$2\frac{1''}{2}\ \frac{1}{4} - 20\ \text{UNC},\ \text{Class 2 or } 2\frac{1''}{2}\ \frac{1}{4} - 20\ \text{UNRC},\ \text{Class 2}$$

50 mm 10 MC (2 mm pitch), Class 2 or 50 mm 10 MJC (2 mm pitch), Class 2

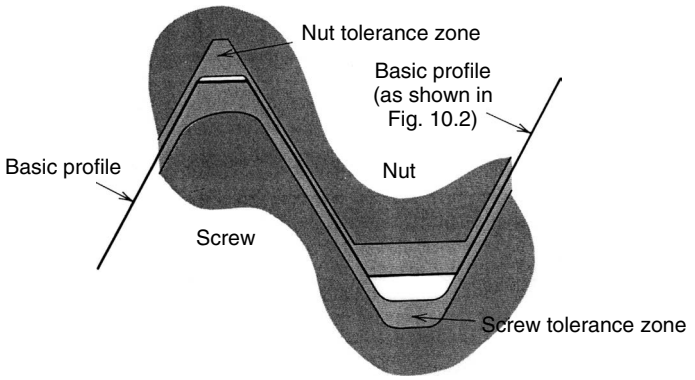

Figure 3.9 Schematic illustration that compares threads with different coarsenesses. (Reprinted from *Fundamentals of Machine Component Design*, R.C. Juvinall and K.M. Marshek, John Wiley & Sons, Inc., New York, NY, 1991, Figure 10.3, page 343, with permission.)

For the former, the bolt has an overall length of $2\frac{1}{2}$ inches, the nominal diameter is $\frac{1}{4}$ inch, and there are 20 coarse threads per inch with a normal fit. For the latter, the bolt has an overall length of 50 millimeters, the nominal diameter is 10 millimeters, and the thread pitch is 2 millimeters per revolution for coarse threads that offer a normal fit.

The pitch of a thread can be "right-handed" or "left-handed." For a right-handed thread, which is by far, the most common, tightening occurs when the fastener is turned clockwise (which tends to be the natural way a right-handed person turns a threaded fastener). For left-handed threads, tightening occurs when the fastener is turned counter-clockwise. Left-handed threads are most often used to prevent or hinder accidental loosening (due to clockwise rotation of a wheel, for example), or to alert the installer to a special situation or to error-proof, such as connections on welding fuel gas versus oxygen-supply lines (see Chapter 6, Subsection 6.4.2).

3.3.3 Bolts

Bolts are almost certainly the best known and probably the most widely used threaded fastener. They are usually two-piece threaded fasteners that develop a clamping force in a joint using a second, internally threaded backup piece called a "nut," which operates on the externally threaded shank of the bolt (see Figure 3.10). Bolts can also be used without a nut, in which case the most distant joint element is internally threaded to accept the bolt.

The critical dimensions on a bolt (besides those specifying its threads) are the nominal diameter of its threaded shaft and its length. Bolts are usually forged and cold-headed for strength and toughness, and the unthreaded portion of the shank is usually machined or ground in one or more places (or over its entire length) to a

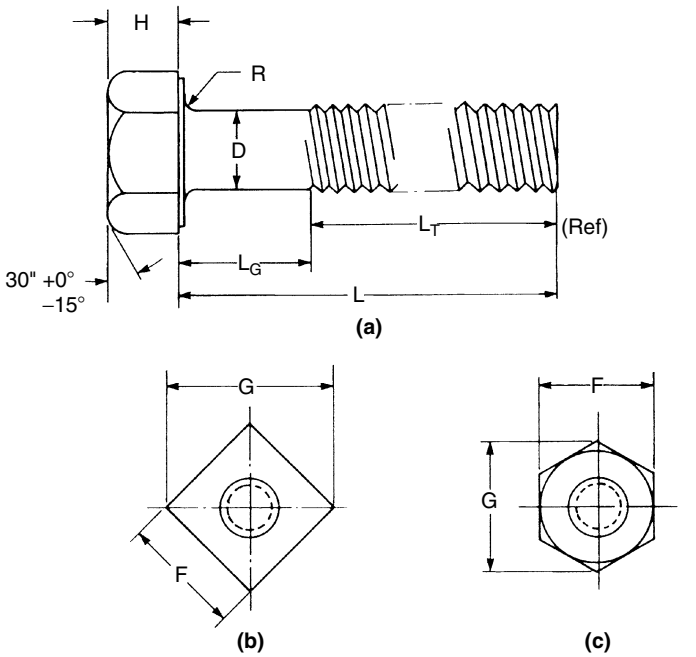

Figure 3.10 Schematic illustration showing the dimensioning of the threaded length of a bolt (a), and the two most common types of nuts, that is square (b) and hexagonal (c). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.4, page 70, with permission of Elsevier Science, Burlington, MA.)

diameter approximately that of its thread-root diameter. The basic threaded length of a bolt is (as shown in Figure 3.10):

$$L_T = 2D + 0.25 \text{ in. for } L < 6 \text{ in.} \qquad L_T = 2D + 6\,\text{mm for } L < 125\,\text{mm},\ D < 48\,\text{mm}$$

$$L_T = 2D + 0.50 \text{ in. for } L > 6 \text{ in.} \qquad L_T = 2D + 12\,\text{mm for } 125 > L > 200\,\text{mm}$$

$$L_T = 2D + 25\,\text{mm for } L > 200\,\text{mm}$$

where L is the length of the bolt under the head and L_T is the threaded length. Of course, D is the nominal diameter of the bolt.

Bolts are classified by their head type, with three head types predominating as shown in Figure 3.11: (1) square head; (2) hexagonal (or hex) head; and (3) round head (or carriage type). Hex-heads can be either (a) heavy structural or (b) finished, and carriage bolts can have various neck shapes (just under their heads) as shown in Figure 3.12. Dimensions of square-heads, hex-heads, and various round-head bolts are contained in ANSI B18.5. The advantage of hex-heads over square-heads is easier access for a wrench in close quarters. The square head tends to allow more tightening. The round-headed carriage bolt is used most often with wood and is designed for a neat, finished look. There are other less common head types, including countersunk (for installation with screw- or socket-drivers), T (for easy hand- or hand-tool tightening),

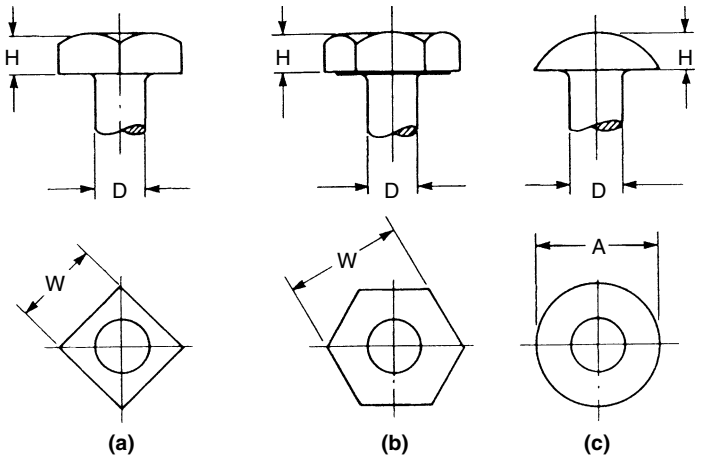

Figure 3.11 Schematic illustration of the three predominant head types used on bolts: square heads (a), hexagonal (or hex) heads (b), and round heads (c). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.5, page 71, with permission of Elsevier Science, Burlington, MA.)

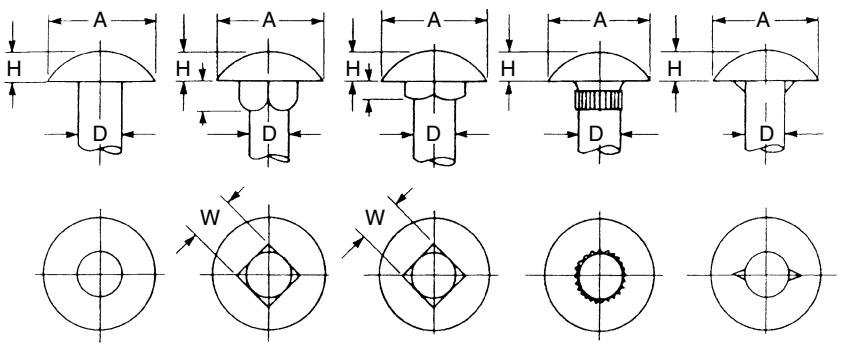

Figure 3.12 Schematic illustration of the most common neck designs found in carriage bolts. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.6, page 71, with permission of Elsevier Science, Burlington, MA.)

askew (for use on slanted, angled, or inclined surfaces), elliptical or oval (as variations of the round-head carriage bolt), as well as eyebolts (for easily attaching other things, such as ropes, hooks, etc.) and bent- or hook-bolts (also for allowing easy attachment of other things). Figure 3.13 shows several special bolt head types.

Grade markings found on the heads of most bolts (and on the heads of all high-quality/high-performance bolts) indicate the material from which the bolt is made and the strength level to which that material is heat treated. A complete listing of grade markings is available in ANSI B18.2-1, published by the American Society forMechanical Engineers. A summary of some of the more important grade markings is given in Table 3.3.

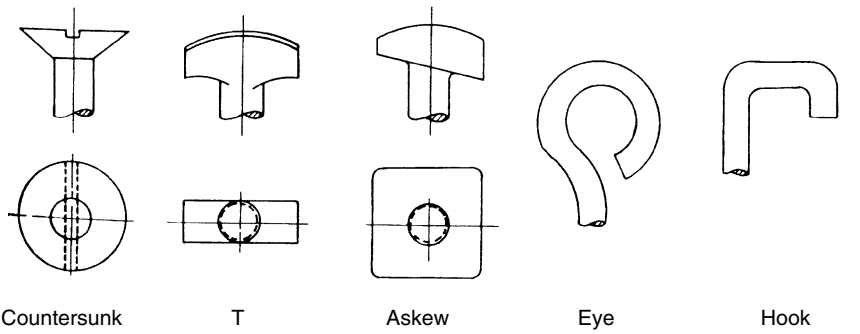

Figure 3.13 Schematic illustration of several special bolt types by head design. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.7, page 71, with permission of Elsevier Science, Burlington, MA.)

3.3.4 Screws

Fasteners referred to as "screws" actually fall into two major categories: (1) *screws* (typified by machine screws) and (2) *tapping* or *self-tapping screws* (typified by wood screws). Screws discussed in this subsection resemble bolts; they are threaded along all or most of their cylindrical bodies. Like bolts, they may use nuts or they may be threaded into an internally threaded part (usually, but not always, only the most distant or back-side part). Because of this, they can be (and are intended to be) used in tension-loaded joints because of their ability to develop a joint clamping force or joint preload. They can also be used without risk to resist shear in shear-loaded joints of either the bearing type or friction type (which, like tension-loaded joints, require the development of a clamping force on the joint elements). The only distinguishing characteristic of screws compared to bolts seems to be their size, which is always smaller than bolts in both diameter and length. Hence, the threads on screws tend to be finer (i.e., have a smaller pitch), with F and EF types occurring for both the Unified Inch and Metric Series. All are manufactured in compliance with the standards shown in Table 3.2. In fact, screws are generally made from the same materials and to the same material specifications as bolts, so they may even have the same identifying head markings. In this sense they are small cousins of bolts.

Like bolts, screws are classified by their head type, but many more head types tend to exist. These include hexagonal heads, square heads, round heads, flat heads and oval heads (the latter two intended for insertion into countersunk holes to make the head fully or nearly flush with the workpiece surface, respectively), hexagonal socket and spline socket heads, as well as several varieties (e.g., cap heads, fillister heads, binding heads, truss heads, and thumb heads) for special purposes. There is also a special type called a "set screw" often used down inside an access hole to tighten a collar or other external part around a shaft or other internal part. The set screw is unique in that its head has the same diameter as its threads. Figure 3.14 schematically illustrates a number of different head types for screws.

Table 3.3 ASTM and SAE Grade Markings for Steel Bolts and Screws*

Grade Marking	Specification	Material
NO MARK	SAE–Grade 1	Low or Medium Carbon Steel
	ASTM–A 307	Low Carbon Steel
	SAE–Grade 2	Low or Medium Carbon Steel
	SAE–Grade 5	Medium Carbon Steel, Quenched and Tempered
	ASTM–A 449	
	SAE–Grade 5.2	Low Carbon Martensite Steel, Quenched and Tempered
	ASTM–A 325 Type 1	Medium Carbon Steel, Quenched and Tempered
	ASTM–A 325 Type 2	Low Carbon Martensite Steel, Quenched and Tempered
	ASTM–A 325 Type 3	Atmospheric Corrosion (Weathering) Steel, Quenched and Tempered
	ASTM–A 354 Grade BB	Low Alloy Steel, Quenched and Tempered
	ASTM–A 354 Grade BC	Low Alloy Steel, Quenched and Tempered
	SAE–Grade 7	Medium Carbon Alloy Steel, Quenched and Tempered, Roll Threaded After Heat Treatment
	SAE–Grade 8	Medium Carbon Alloy Steel, Quenched and Tempered
	ASTM–A 354 Grade BD	Alloy Steel, Quenched and Tempered
	ASTM–A 490	Alloy Steel, Quenched and Tempered

ASTM Standards:
A 307–Low Carbon Steel Externally and Internally Threaded Standard Fasteners.
A 325–High Strength Steel Bolts for Sructural Steel Joints, Including Suitable Nuts and Plain Hardened Washers.
A 449–Quenched and Tempered Steel Bolts and Studs.
A 354–Quenched and Tempered Alloy Steel Bolts and Studs with Suitable Nuts.
A 490–Quenched and Tempered Alloy Steel Bolts for Structural Steel Joints.
SAE Standard:
J 429–Mechanical and Quality Requirements for Externally Threaded Fasteners.
Source: ANSI B18.2.1-1972, as published by the American Society of Mechanical Engineers.

*Adapted from Robert O. Parmley's *Standard Handbook of Fastening and Joining,* 2nd ed., McGraw-Hill, 1989, with permission. Source: ANSI B18.2.1-1981 (R92), Appendix III, p. 41, by permission.

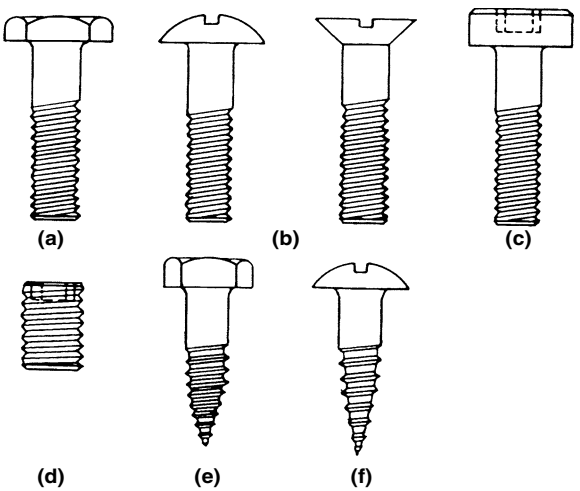

Figure 3.14 Schematic illustration of a number of different types for screws, predominantly differing in the type of head, including (a) hexagonal- (hex-) or square-head cap screw; (b) slotted round (also ellipse or oval) and countersunk cap screws; (c) recessed socket-head cap screws (of various socket designs); (d) socket-head set screw; (e) hex- or square-head lag bolt; and (f) slotted-head self-tapping screw. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.8, page 73, with permission of Elsevier Science, Burlington, MA.)

Some screws, such as hexagonal-head and square-head types, are intended to be tightened by applying some type of wrench to the outside of the head. Others, such as hexagonal-socket and spline-socket heads, are intended to be tightened using a device (e.g., a socket driver) that inserts into a socket recessed into the head. Still others are intended to be tightened or "driven" with a tool (e.g., a screwdriver) that inserts into a slot into the head; examples of these are round, flat, fillister, oval, truss, cap, and binding heads. The slots themselves can be a simple groove (called a "slot") that traverses the head, or crossed slots that produce a so-called "Phillips" head (of which there are actually several varieties). There are also some special head designs that have been developed to be tamper resistant by anyone but an authorized mechanic. These employ specially designed slots or sockets or protrusions requiring special driving and loosening tools. Some examples are shown in Figure 3.15. A comprehensive list of the various head types is as follows:

1. Hex-head cap, heavy, and finned screws
2. Socket heads, including hex, forged spline, low, button-head, shoulder, flat-head, pressure plug, and set cap screw varieties
3. Slotted-head, flat-countersunk, and fillister-head cap screws
4. Machine screws with regular or undercut, slotted or cross-recessed, 80-degree or 100-degree, and flat or oval countersunk heads; 100-degree flat countersunk heads; flat or oval countersunk trim heads; pan, fillister, truss, binding, or hex heads; and (integral) hex-washer heads

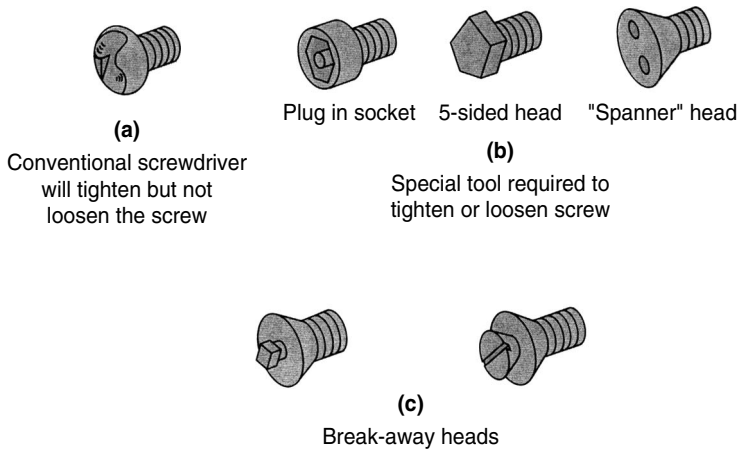

Figure 3.15 Schematic illustration of some ''tamper resistant'' screws. (Reprinted from *Fundamentals of Machine Component Design*, R.C. Juvinall and K.M. Marshek, John Wiley & Sons, Inc., New York, NY, 1991, Figure 10.17, page 362, with permission.)

3.3.5 Nuts and Lock Nuts

A nut is a block of material (often a metal, generally the same as the metal used in the mating bolt or screw) that usually has a square or hexagonal peripheral shape with an internally threaded hole drilled and tapped through its center. It is intended to mate with a standard externally threaded bolt or screw (or integral stud, as described in Section 3.5), and is used to develop a clamping force on a joint by moving along the threaded shaft of the bolt or screw (or integral threaded stud) to oppose the force applied by the head (or part, for a threaded integral stud) upon tightening. Usually the nut is a separate piece used for backing a bolt or screw (or threaded integral stud), but occasionally nuts are attached (e.g., as plate nuts) or are integral to the joint element or other part.

Nuts are available in several standardized designs (see Subsection 3.3.7 for specifications), including square nuts, hexagonal nuts, slotted and castle nuts, and wing nuts, as well as a variety of special ''lock nuts'' (to be described below). Examples of various common or standardized types are schematically illustrated in Figure 3.16.

Many methods have been devised to prevent nuts from loosening under service loads (especially, but not only, vibrations). The oldest (and quite successful, but sometimes labor intensive, awkward, or bulky) methods involve pinning through a hole in the body of the nut with a wire or straight, tapered, or Cotter pin (see Subsection 3.4.4). Other methods include (1) using a second nut (a so-called ''jam nut'') to interfere with the first regular nut; (2) staking (see Subsection 3.6.2) or ''prick-punching'' the exposed thread below the nut (on the exposed face) at one or more points after assembly; (3) adding a drop of adhesive or locking compound between the threads at the outer surface of the nut where the bolt or screw enters or exits the nut; and (4) using off-angle threads in the nut or on the bolt to cause plastic deformation and interference between the male and female threads. A special type of nut, called a *lock nut*, resists loosening

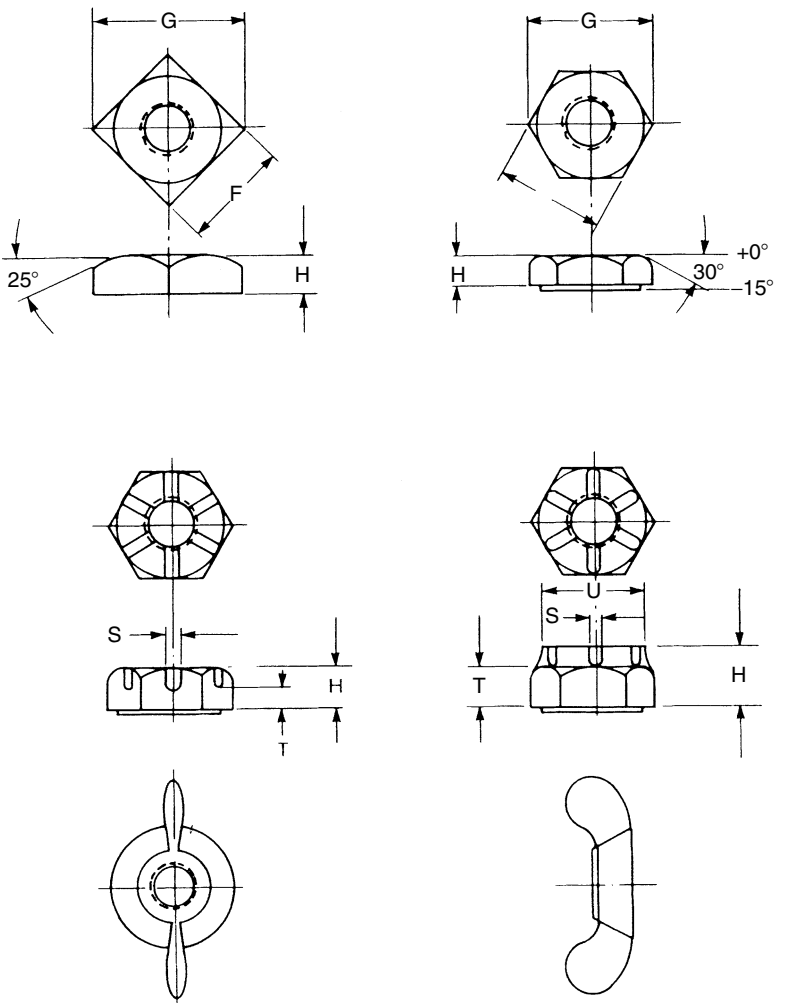

Figure 3.16 Schematic illustration of some important standardized nut designs. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.10, page 76, with permission of Elsevier Science, Burlington, MA.)

through its inherent design. Two major subclasses of lock nuts exist: (1) nuts that lock themselves to the thread of the bolt or screw through interference developed between external and internal threads; and (2) nuts that are free-turning until they engage a bearing surface on the bolt or screw shank that causes a locking action.

Several common design approaches are used in lock nuts. One approach uses an insert made of a soft, resilient[8] material (such as lead, nylon, or resin-impregnated

[8] The term "resilient" used in this context means capable of repeated elastic recovery after an applied load is released.

fiber) through which the bolt or screw must form its own threads by elastic or plastic (actually, combined elastic–plastic) deformation. For nuts of this type, the bolt or screw must be driven to its final assembled position, but because of the resiliency of the soft insert material, disassembly and reassembly can be done repeatedly. In another approach, nuts are made with a few threads near their outer surface (i.e., face farthest from the bolt or screw head) that have been deformed radially to produce a slight oval shape. Or the pitch (''lead-angle'') of the threads might be altered to grip the bolt or screw threads when assembled. A third approach uses any of several designs where the nut is shaped to take advantage of the spring properties (i.e., elastic limit strength and modulus of elasticity) of the material from which it is made, including sheet metal nuts and nuts with slotted segments. Finally, there are nuts that develop a wedging action between an inner and an outer sleeve, tapered so that the inner threaded part is compressed into the threads of the bolt or screw by the outer sleeve. Examples of some lock-nut designs are schematically illustrated in Figure 3.17.

These types of lock nuts are available under various trade names, such as Nylok (with a nylon insert), McClean-Fogg #3 (with an altered pitch), Tri-Lok (with an oval or elliptical thread), Flexlok (with spring action from slotted segments), Tinnerman speed nuts (with spring action from their sheet metal construction), and Klincher (which develop wedging actions between sleeves).

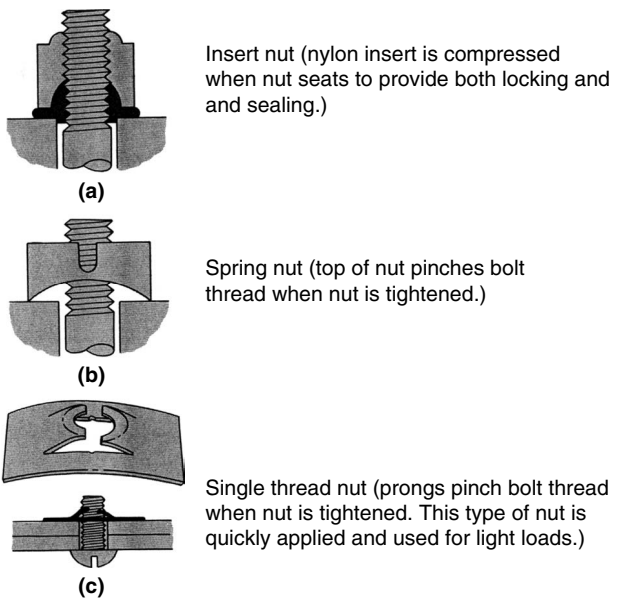
Insert nut (nylon insert is compressed when nut seats to provide both locking and and sealing.)
(a)
Spring nut (top of nut pinches bolt thread when nut is tightened.)
(b)
Single thread nut (prongs pinch bolt thread when nut is tightened. This type of nut is quickly applied and used for light loads.)
(c)

Figure 3.17 Schematic illustration of some lock-nut designs. (Reprinted from *Fundamentals of Machine Component Design*, R.C. Juvinall and K.M. Marshek, John Wiley & Sons, Inc., New York, NY, 1991, Figure 10.22, page 370, with permission.)

3.3.6 Tapping or Self-Tapping Screws

Tapping or *self-tapping screws* are the second major category of screws. Unlike simple screws (typified by "machine screws"), self-tapping screws develop a clamping action in a joint through the gripping and friction between the screw and the part as the screw forces its way into the part by creating its own mating female threads as it goes. No internal threading of the part or use of a supplemental nut, and usually no predrilling of a hole, is required.

Tapping screws are actually of three main types, classified by the way in which they produce the threaded path in the material into which they are inserted to cause fastening: (1) "thread-forming," (2) "thread-cutting," and (3) "thread-rolling" types. *Thread-forming screws* are used when sufficient joint stresses can be developed to guard against loosening. These screws literally form the mating thread in the part or joint element being fastened by plastically deforming the part or joint element. Gripping of the screw's threads over their large surface area comes from the combination of the elastic recovery force squeezing on the screw threads and the friction arising from microscopic asperities on the mating screw and part surfaces. Part or joint materials for which this type of tapping screw is suitable include wood, soft metals (e.g., aluminum, copper, zinc, lead, and tin alloys), and elastic or compliant polymers (especially, but not only, thermoplastics). Various specific thread designs are schematically illustrated in Figure 3.18a. *Thread-cutting screws* are used instead of thread-forming screws to lessen the force needed for tapping the thread and to simultaneously lessen the resulting residual stresses that could, by being tensile in nature, contribute to fatigue as well as corrosion. Rather than forming threads into the joint material by plastic deformation, these screws produce mating threads by a cutting action. Part or joint element materials suited to this type of tapping screw include harder, more brittle metals (e.g., cast magnesium alloys, cast iron, zinc die–cast), harder polymers (usually, but not only, thermosets), and even ceramics (including cement and concrete). Figure 3.18b shows some specific designs for this type of thread. *Thread-rolling screws,* like thread-forming screws, deform threads into the material(s) being fastened, but induce significant cold work and compressive residual stresses into these materials during tapping, thereby contributing to joint strength, especially in fatigue. Part or joint element materials suited to these screws include high-strength metals (e.g., steels, titanium alloys, and some Ni- or Co-based superalloys) and hard, resilient thermoplastic or thermosetting polymers.

3.3.7 Materials and Standards for Major Types of Threaded Fasteners

Bolts, screws, nuts, and self-tapping screws are generally made from low- or medium-carbon steels, low alloy steels, medium-carbon alloy steels, high alloy steels (often in their quenched and tempered conditions, where applicable), and from stainless steels. For certain applications, special materials such as brasses, bronzes, nickel–copper alloys, and titanium alloys have been used. These fasteners are also generally manufactured to standards such as those published by the American National Standards Institute (ANSI). A

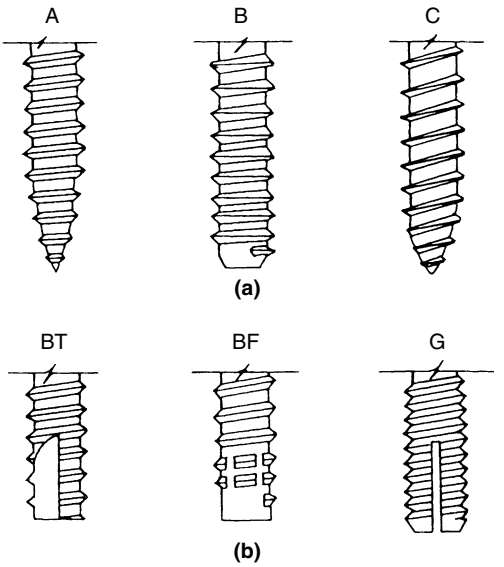

Figure 3.18 Schematic illustration of (a) "thread-forming" and (b) "thread-cutting" self-tapping screws. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.11, page 77, with permission of Elsevier Science, Burlington, MA.)

list of standards is given in Table 3.2. Tapping screws, also made to ANSI standards, can be made from aluminum alloys and other specialty materials. All types of threaded fasteners can be made from specialty materials for special applications, with examples being nylon and even reinforced plastic (resin) bolts and nuts, machinable engineered-ceramic bolts and nuts, and Ni- or Co-based superalloys, refractory metals or alloys, and others.

Recall that grade markings are placed on the heads of many bolts and screws, especially those intended for demanding applications. These markings were shown in Table 3.3.

3.3.8 Integral Fasteners and Self-Clinching Fasteners

There are two special forms of threaded fasteners beyond the normal and much more common bolts, screws, nuts, and tapping screws that deserve mentioning. These two are "integral fasteners" and "self-clinching fasteners."

An *integral fastener* is a device, usually threaded, that is installed into a component or unit (such as an automobile or truck chassis, an aircraft or spacecraft, or even an appliance or furniture panel) to become a permanent or semi-permanent part of that component or unit. Such permanently mounted fasteners are used because they facilitate subsequent, often automated, assembly, they are dependable in service (i.e., they cannot be lost), and they are generally quite cost effective because of how they facilitate manufacturing or assembly. Permanently mounted fasteners can be mechanically clinched, swagged, riveted, welded, brazed, or adhesive-bonded in place, or may be of a self-

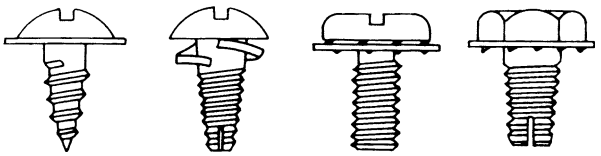

Figure 3.19 Schematic illustration of a few examples of integral screw-washer fasteners known as "sems." (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.12, page 78, with permission of Elsevier Science, Burlington, MA.)

clinching or self-mounting design. Such integral fasteners are available in hundreds of designs and sizes, which could be considered the "good news and the bad news!"

One significant type of threaded integral fasteners is "sems." Sems are a combination of various standard screws and a captive (as opposed to truly integral) washer. Such screw–washer assemblies or sems are used for convenience in assembly because they combine two small parts into one that is much easier to handle, with much less of a chance of failing to install the washer. This is particularly advantageous for automated fastening or assembly. Figure 3.19 schematically illustrates a few examples of sems.

Another common and important example of an integral threaded fastener is the anchor-type or plate-type "anchor nut" or "plate nut." These integral fasteners are usually installed by riveting a plate or housing that holds an internally threaded body or nut. Thermal staking (see Subsection 3.6.2) or adhesive bonding are other possible mounting methods for such nuts. Often the body or nut has some freedom to move within a limited range fixed by the plate that "captures" the nut. This freedom is useful for compensating for slight misalignments caused by ever-present tolerance stackup during manufacturing. A normal threaded bolt or screw is inserted into the plate nut, mating with the permanently anchored nut.

Other types of integral fasteners include clinch nuts, weld nuts, welded studs (see "stud welding" in Chapter 6), and various two-piece assembled rivets and pins (such as those used in the do-it-yourself assembly of wooden furniture).

Self-clinching fasteners are particularly attractive integral fasteners, providing assembly and service economies as well as cosmetic benefits. Self-clinching fasteners are squeezed into a preplaced, previously fabricated hole in a sheet metal or plastic part, for example, using a simple press. The sheet metal or plastic, which must always be softer than the fastener, plastically deforms into an annular groove around the perimeter of the clinch fastener collar or body under the installation pressure. A typical installation is shown schematically in Figure 3.20. A strong, permanent fit is ensured by such fasteners even if very thin (e.g., 0.020 in. (0.5 mm)) sheet metal or plastic is used.

Several fairly standard self-clinching fasteners include nuts with free-floating or self-locking threads; self-locking or non-self-locking floating insert nuts; flush-head, heavy-head, and concealed-head studs; through-hole, blind-hole, and concealed-head standoffs; panel fasteners with captive screws; spring-loaded pins; flush-head pins; and electrical grounding solder terminals.

Table 3.4 lists the major types and subtypes of threaded fasteners.

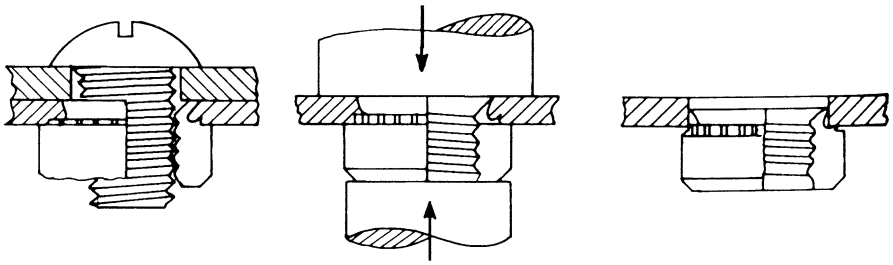

Figure 3.20 Schematic illustration of the installation of a self-clinching fastener. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.13, page 78, with permission of Elsevier Science, Burlington, MA.)

Table 3.4 Major Types and Subtypes of Threaded Fasteners

Bolts
Square-headed bolts
Hexagonal- (Hex-) headed bolts
Round-headed (carriage) bolts
Eye-bolts and other special head types (e.g., hooks)
Nuts
Square nuts
Hexagonal (hex) nuts
Castle nuts
Lock nuts (of various types)
Plate nuts
Anchor nuts
Self-clinching nuts
Screws
Machine screws or simply "screws" (with various head types)
Set screws (including "Allen" screws)
Tapping or self-tapping screws (with various head and thread types)
Others
Lag bolts or lag screws (which tap their own holes)
Spring-type ("Molly") anchor bolts
Threaded studs (welded onto or cemented into a base)
Threaded rods (to be used with multiple nuts)

3.4 UNTHREADED FASTENERS

3.4.1 General Description of Unthreaded Fasteners

Not all fasteners require threads to achieve interlocking between or among joint elements. *Unthreaded fasteners* accomplish interlocking through some means other than the clamping force produced by a thread (actually opposing threads!). The mechanism by

which such fasteners cause interlocking, produce interference, and give rise to joining may involve simple pinning, relying on varying degrees of bearing or friction—or both—between the fastener and the joint element. Other possible mechanisms are some elastic spring action in the fastener (or possibly the joint), or plastic deformation of the fastener. Unthreaded fasteners can be used in shear- or tension-loaded joints, but they are almost always intended for use in shear, acting principally as pinning points.

Unthreaded fasteners include (1) upsetting rivets, (2) blind rivets (or blind fasteners), (3) pins (which includes pegs and nails), (4) eyelets and grommets (the latter commonly referred to as "snaps"), (5) retaining rings or clips, (6) keys with keyways, and (7) washers and lock-washers. Most unthreaded fasteners require pre-prepared holes (for upsetting and blind rivets, pins, and eyelets/grommets), grooves (for retaining rings or clips), or slots or keyways (for keys). Washers that are used with other fasteners (mostly bolts, screws, and nuts) do not require special pre-preparation of any kind. Occasionally, depending on the material in which they are used, even eyelets/grommets (see Subsection 3.4.6) do not require pre-preparation of holes because they can be caused to make their own holes as they are installed.

Besides these well recognized types of unthreaded fasteners, there are many unthreaded fasteners that, while common, are less well known as actual fasteners. Table 3.5 lists the major and less well known types of unthreaded fasteners.

3.4.2 Upsetting Rivets

Rivets are fasteners without threads (i.e., unthreaded fasteners) that are installed into a material part or joint element (often into a pre-prepared hole, but not necessarily!). Most rivets are locked into place or "set" by using an existing "head" and creating a "foot." A few types, however, create both a head and a foot. The body or shank of all rivets is generally cylindrical, and the shank is intentionally smaller in diameter than the head and foot to allow the rivet to be locked in place by these features. Two broad classes of rivets exist: (1) those that are plastically deformed to create at least the foot on a headed shank and sometimes both a head and a foot or two heads to lock or set the rivet in place; and (2) those that lock themselves into place using special design features to create a foot or that have a foot or "backing piece" added as part of the rivet's installation. The former are called "upset rivets" and the latter are called either "blind rivets" or "two-piece rivets." All rivets are ideal for (and, in fact, are designed for) carrying loads in shear through bearing between the rivet's shank and the joint element(s).

Upsetting rivets are made from a plastically deformable material (e.g., a metal or thermoplastic). They are used to join several parts or elements together by placing the rivet's shank (with or without a head) through pre-prepared holes in parts that are properly aligned; they then create a second head or foot by plastically deforming or upsetting the projecting shank. Depending on the rivet material, upsetting can usually be done cold (i.e., at room temperature) but may need to be done while the rivet is in its hot-working range to reduce the forces needed to cause upsetting and to increase the material's ductility or malleability. Hot-upsetting rivets are usually made from steel and are of large diameter. Such hot-forming rivets were widely used in the erection of

Table 3.5 Major and Less Well Recognized Unthreaded Fasteners

Major Types (Well Recognized as Unthreaded Fasteners):
- Rivets
  - Upsetting rivets (headed and headless, "slug" one-piece rivets)
  - Self-setting (two-piece) or self-upsetting (one-piece) rivets
  - Self-piercing (one-piece) rivets
  - Swagged (two-piece) rivets
  - Blind or "pop" (multi-piece) rivets (of various types, such as Huck, Cherry, etc.)
- Nails, brads, and tacks
- Pegs (of wood)
- Pins
  - Taper pins
  - Spring pins
  - T-pins
  - Cotter pins (which must have their tails bent to hold)
- Washers and lock-washers
- Eyelets/grommets
- Retaining rings and clips
- Keys with keyways

Less Well Recognized Unthreaded Fasteners:
- Staples
- Stitches and sutures
- Laces and lashings
- Knots and splices
- Windings
- Hook-and-loop fasteners (e.g., DuPont's Velcro and 3M's Dual-Locks)
- Snap-fit fasteners
- Zippers
- Buttons
- Snaps (actually grommets)
- Magnetic fasteners and connections
- Couplings
- Clutches

steel structures for bridges or buildings prior to the 1960s but are less common today. Rivets made from thermoplastics are also "hot set." Figure 3.21 schematically illustrates a typical hot-upsetting rivet before and after upsetting.

Rivets can be upset manually, often by hammering[9] the head while "bucking" the tail to produce the foot or second head, or by using automatic squeezing machines or mechanisms. The most common of these are C-frame machines that apply either a slow squeezing force or a rapid forging force on the head and tail simultaneously. Because of the forged (often cold-worked) grain structure that results in metal rivets,

[9] So-called "riveting guns" are used, which apply a rapidly repeated hammering (through one of several means, usually using pneumatics) to impart a force and elastic shock-wave in the rivet's shank (through its head) that causes the tail-end of its projecting shank to bang against a steel bucking bar (often containing a shaped recess to shape the upset "foot") and undergo plastic deformation.

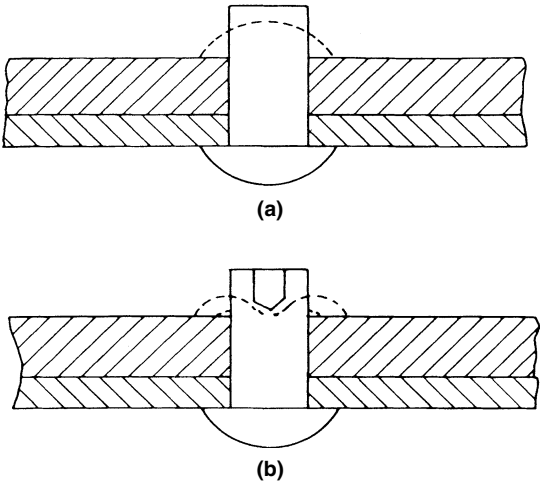

Figure 3.21 Schematic illustration of a typical upsetting rivet before and after upsetting or "setting"; (a) solid and (b) tubular varieties. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.14, page 81, with permission of Elsevier Science, Burlington, MA.)

most metal rivets tend to have higher tensile, compressive, and shear strengths than many other fasteners. Thermoplastic rivets are "set" using a heated plate to hot-form the foot at the rivet's projecting tail.

There are some two-piece rivets, usually used for higher strength applications such as aerospace, in which a malleable collar or retaining piece is formed (usually swaged), clinched, or otherwise attached to a high-strength projecting shank with an annular receiving groove. These are called "high-shear rivets."

Rivets in general, and upsetting rivets in particular, offer some advantages that are unique among all mechanical fasteners. These advantages include (1) low fabrication cost (because at least the upsetting types are geometrically simple and can be produced in large quantities by high-speed machines); (2) low installation cost (because insertion and setting are fast, repetitive, and require relatively little operator skill or can be automated); (3) ability to produce semi-permanent joints (as rivets can be drilled out!) that can be readily inspected immediately upon installation of the rivet (simply by visually checking for cracks, splits, or incomplete setting or upsetting, and permitting corrective action by the operator, if needed); (4) ability to allow relative rotation between parts or joint elements (acting as pivot shafts); (5) ability to join dissimilar materials (such as metals and polymers) of various thicknesses; (6) ability to join as many parts as necessary (as long as the shank is long enough to project through the stack); (7) attractive appearance compared to many other fasteners (because they can be made flush and virtually invisible and may even be used for decorative purposes, such as on leatherwear); (8) ability to offer an aerodynamically smooth contour with the joint element when special countersinking and shaving techniques are used on heads (or heads and upset tails when the tails are created in a countersink); (9) wide diversity of shapes, sizes, and materials; and (10) ability to be installed with a wide variety of methods, tools, and machines.

Despite these many advantages, rivets do have some limitations or even disadvantages, including that (1) they may not be as strong in static tension or fatigue as bolts; (2) they should not be relied upon for developing a clamping force on a joint for either friction type shear-loaded or tension-loaded joints[10]; (3) high enough tensile forces (or stresses) can pull out (or pull off) the cinch or upset, causing the rivet to pull out of the joint; (4) severe vibration can loosen the joint, and retightening by further impact can be difficult; (5) removal for disassembly for any reason (e.g., repair, upgrade, disposal) is more difficult than for threaded fasteners and many other types of unthreaded fasteners (although most, if not all, types can be drilled out); and (6) installation usually requires access to both sides of the joint for all but some very special upsetting rivets and for so-called "blind rivets."

Upsetting rivets can be divided into two major categories, solid and tubular, as far as the shank is concerned. Tubular rivets can themselves be subclassified as full tubular, semi-tubular, compression, and (sometimes) self-piercing. A solid and a tubular rivet are compared in Figure 3.21a and b. Self-piercing and self-upsetting rivets (or other fasteners) will be described later in Subsection 3.4.4.

The most distinguishing feature of upsetting rivets is their head shape, of which there are many, as shown in Figure 3.22. Head shape is usually specific to certain types of intended applications, with the various types including the following:

- *Standard structural or machine rivet:* A solid rivet with a cylindrical shank that is either hot- or cold-driven or upset. The upsetting force depends on the material, size, and temperature of upsetting. These rivets are standardized and available in many materials (e.g., heat-treatable and non-heat-treatable aluminum alloys and magnesium alloys; copper and copper alloys, such as brasses, bronzes, and cupro-nickels; plain carbon, low-alloy, and stainless steels; titanium and titanium alloys; and various thermoplastics).
- *Slug rivet:* A simple, headless cylinder that is inserted into a hole and upset at both ends simultaneously to produce two formed heads or feet.
- *Boiler rivet:* A large, solid rivet having a conical head that was formerly widely used for assembling boilers—pressure tight![11]
- *Cooper's rivet:* A solid rivet used for barrel hoops or barrel hoop joints, having a thin, countersunk head with a chamfered crown and shank end.
- *Shoulder rivet:* A solid rivet with a formed shoulder under the head that is often used for making other attachments.
- *Tank rivet:* A small, solid rivet with button, countersunk, flat, or truss heads used for sheet metal assembly.
- *Tinner's rivet:* A solid rivet with a large flat head used for joining soft and/or thin sheet metal to prevent head pull-through.
- *Belt rivet:* A special solid rivet with a thin collar below the head used for joining leather or fabrics (e.g., denim).

[10] If an upsetting rivet is "hot set," a clamping force can be developed as the hot shank, with its newly formed foot acting with its head, cools and thermally contracts axially. However, the resulting clamping force may not be very reliable.

[11] Boilers have not been assembled using rivets for many years; today they are welded.

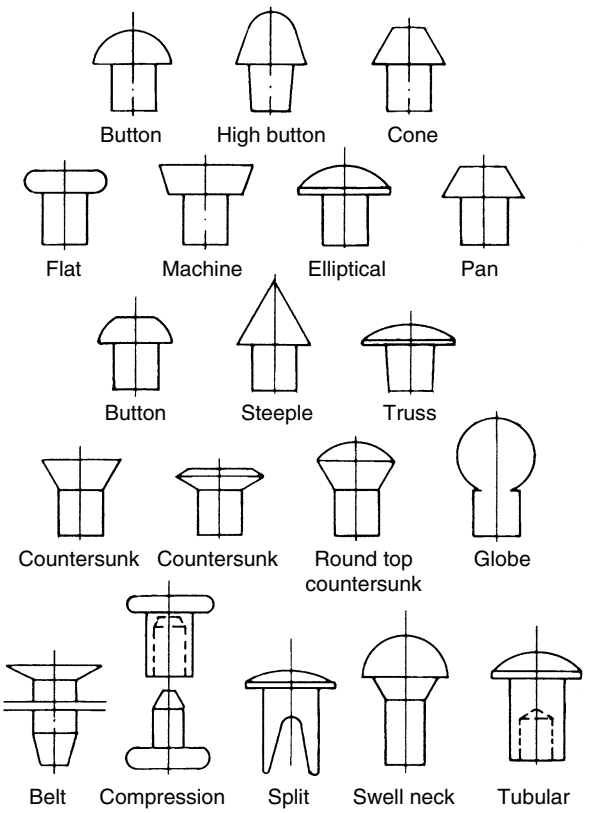

Figure 3.22 Schematic illustration of the various head types found on upsetting rivets. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.15, page 82, with permission of Elsevier Science, Burlington, MA.)

- *Compression or cutlery rivet:* A two-piece rivet consisting of a tubular portion and a mating solid portion. The hole in the shank of the tubular portion is sized to produce a drive- or press-fit when the joint is assembled.
- *Split or bifurcated rivet:* A solid, self-piercing rivet having a prong in the shank that cuts its own hole through soft metals or fibrous materials like cloth and wood.
- *Swell-neck rivet:* A large, solid rivet with a large bulbous head and a swelled neck below the head. It produces a tight fit when set.
- *Tubular rivet:* A small rivet having a hole down the center of the shank at one end. The rivet is cold-driven with a tool that expands or curls the shank end to set the fastener. Hollow or tubular rivets are the basis for several special types of unthreaded fasteners, most especially blind rivets.

Most rivets are standardized under ANSI B18.1.1 (covering small rivets) or B18.1.2 (covering large rivets). Tubular rivets are covered by ANSI B18.7.

A special type of one-piece solid rivet known as a "self-piercing rivet" pushes a rivet made from a strong, hard metal through pieces (including soft metals like Al-alloys) to be joined, creating the hole containing the rivet as the rivet is installed. More is said about these types in Subsection 3.4.4.

Joint designs for rivets of all types are typically single- or double-overlap (or splice-butt) types, and rivets within these joints are arranged (as are bolts and screws in bolted joints) in single, double, and even triple rows of either straight chain or staggered holes, as shown in Figure 3.23.

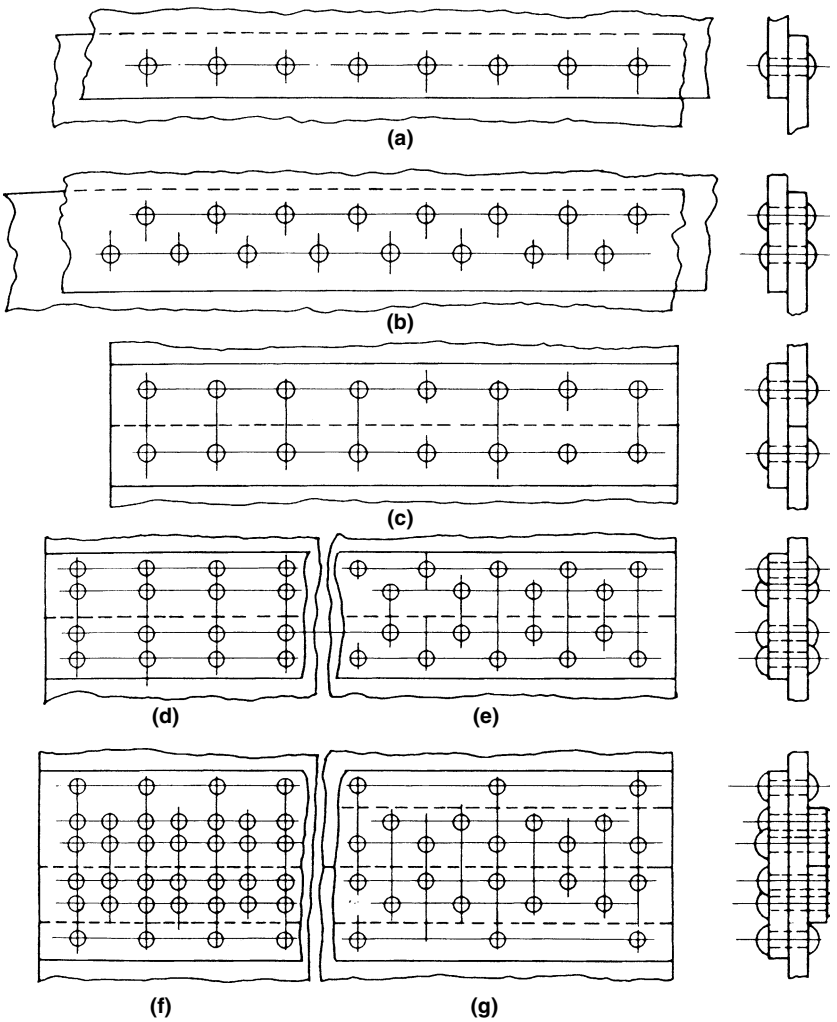

Figure 3.23 Schematic illustration of common single, double, and triple rows of either straight-chain or staggered holes for rivets. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.16, page 83, with permission of Elsevier Science, Burlington, MA.)

3.4.3 Blind Rivets

Blind rivets are a special class of unthreaded fasteners—a subclass of rivets that are among the most innovative of the entire group of unthreaded fasteners in that they enable mechanical joining that would otherwise be impossible. The designs of blind rivets are specifically intended to allow installation and setting of the rivet from one side and are thus invaluable for applications where access to the so-called "blind" side is impossible or impractical. Originally, blind rivets were invented to permit repair of previously riveted joints but since they were strictly a replacement fastener they offered unimpressive mechanical strength! Today, blind rivets and other blind fastener designs have proliferated to fill a much-needed niche in mechanical fastening.

As distinguished from the standard solid rivet, a blind rivet can be inserted and fully installed or set in a joint from one side of a structure or assembly. The back side or blind side of this type of rivet is mechanically expanded to form a bulb or upset "head" or "foot." This can be done using some special design feature of the fastener (usually with a special tool), using a very small explosive charge in a hollow-shank tubular rivet, or using a special transformation (e.g., shape memory) in the rivet material. In any case, the result is a permanently installed fastener that duplicates and sometimes exceeds the performance criteria for comparable solid rivets. Figure 3.21 shows how a conventional solid rivet requires access to both sides of a joint to permit installation. Figure 3.24 schematically illustrates several typical situations that prohibit back side accessibility and, therefore, benefit from blind rivets.

Figures 3.25 and 3.26 show examples of some of the principles used in blind rivets to allow them to be set. Special tools, usually designed and produced by the same company that designed the blind fastener, are used to install and set these rivets. Some of the more common types of blind fasteners are Chobert rivets, Huck rivets or fasteners, Cherry rivets, rivnuts, explosive rivets, Southco rivets, and pop-rivets.

The Chobert rivet (Figure 3.25a) is upset or set by drawing a solid high-strength material mandrel through a tapered hole in a soft metal locking piece, leaving what is essentially a tubular rivet to fasten the joint. The Huck rivet (manufactured by the Huck Manufacturing Company) is similar to the Chobert in that it is also tubular. However, after the mandrel or high-strength material pin is pulled through the soft metal sleeve or collar to set the rivet by forming a tailpiece, it is broken off at a preplaced notch or groove to produce a stronger solid rivet (Figure 3.25b). There are, in fact, several variations of the Huck rivet, including lock-bolts, self-plugging blind rivets, and pull-through blind rivets. The Cherry rivet (manufactured by the Cherry Rivet division of Textron) is available in three designs: regular hollow, pull-through, and self-plugging. The regular hollow rivet is used when a high clamping force is desired, where the amount of shank expansion is not a factor, and where the presence of broken-off stem pieces entrapped in the assembly after fastening is not objectionable.[12] The Cherry pull-through rivet is useful where the broken-off stem falling into the assembly is

[12] Broken-off pieces are unacceptable in many applications where they could move around and become trapped and interfere with some mechanism. The aerospace industry refers to such unacceptable debris as FOD—"foreign object debris."

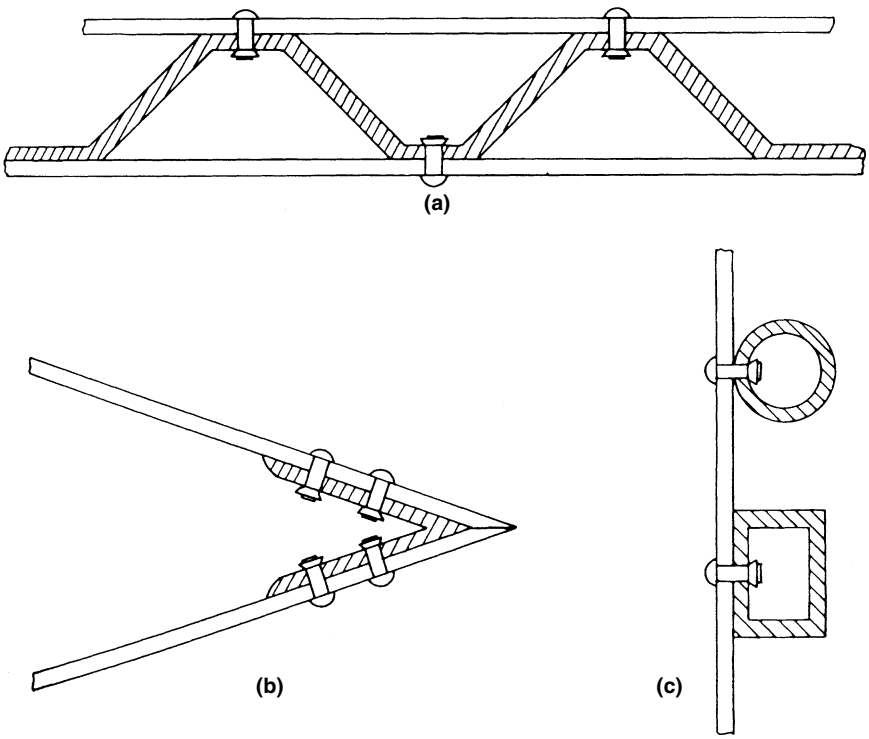

Figure 3.24 Schematic illustration of several situations that prohibit back-side accessibility and, therefore, benefit from blind rivets. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.18, page 85, with permission of Elsevier Science, Burlington, MA.)

objectionable (e.g., aircraft or spacecraft), but where lower clamping or clinching force is tolerable. Where a hollow rivet is unacceptable because of high loading, the self-plugging Cherry rivet is used. These three types are shown in Figure 3.25c.

It is important and useful to note that several of these blind rivets are actually designed to produce a clamping force on a joint and can thus be considered for friction-type shear-loaded or tension-loaded joints. One needs to recognize, however, that the level of clamping force that can be obtained (and the reliability of it not being lost over time in service) needs to be carefully considered before resorting to these unthreaded fasteners instead of threaded bolts and screws, with or without nuts.

Besides these proprietary, commercially available types of fasteners, there are generic rivnuts and explosive rivets. The rivnut is set by pulling on a threaded pull-up stud that collapses the hollow shank of the fastener to clinch the joint. Figure 3.26a shows the operation of rivnuts. A related type is the Southco rivet, shown in Figure 3.26b. These rivets form a hollow shank into a locking shape by driving a pin extending out of the head through the shank. Southco rivets are known generically as "drive pin" rivets. While by no means typical blind fasteners, some rivets can be installed

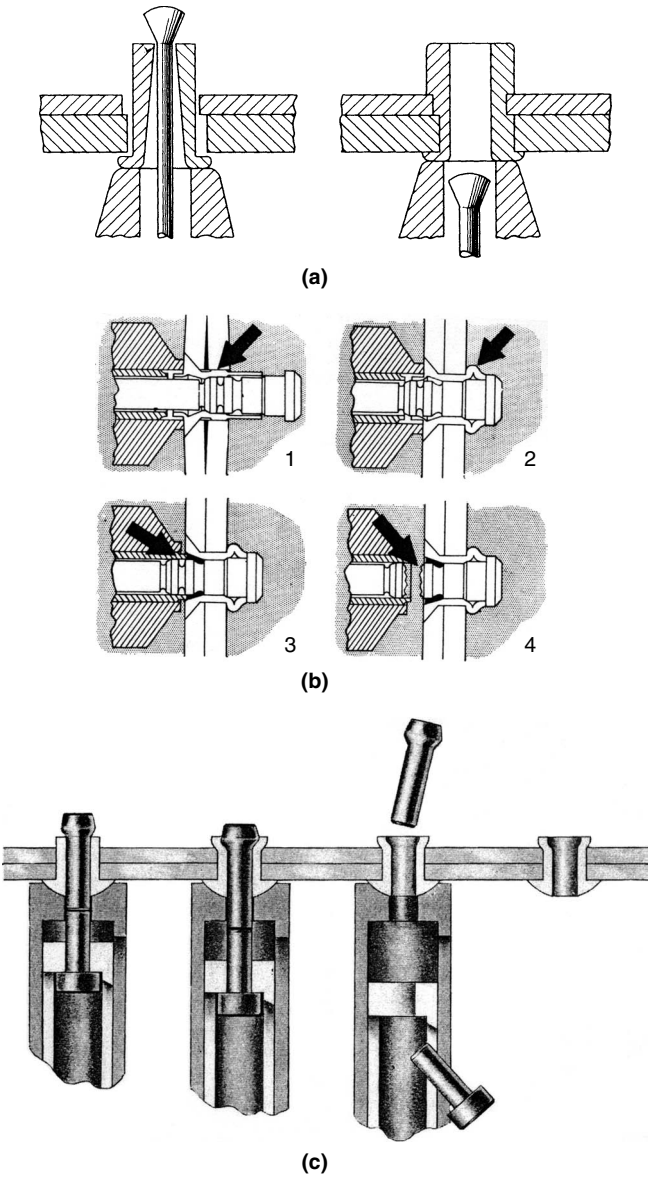

Figure 3.25 Operation of some popular blind rivets; including Chobert (a), Huck (b), and Cherry (c) designs. (Reprinted from *Handbook of Fastening and Joining of Metal Parts*, V. Laughner and A. Hargan, Figures 5.13, 5.15, and 5.22, pages 209, 210, and 214, McGraw-Hill Publishing, New York, NY, 1956, with permission.)

(i.e., upset) using a small explosive charge embedded in their hollow shanks. By detonating the explosive with heat, electricity, or high-speed impact, the hollow

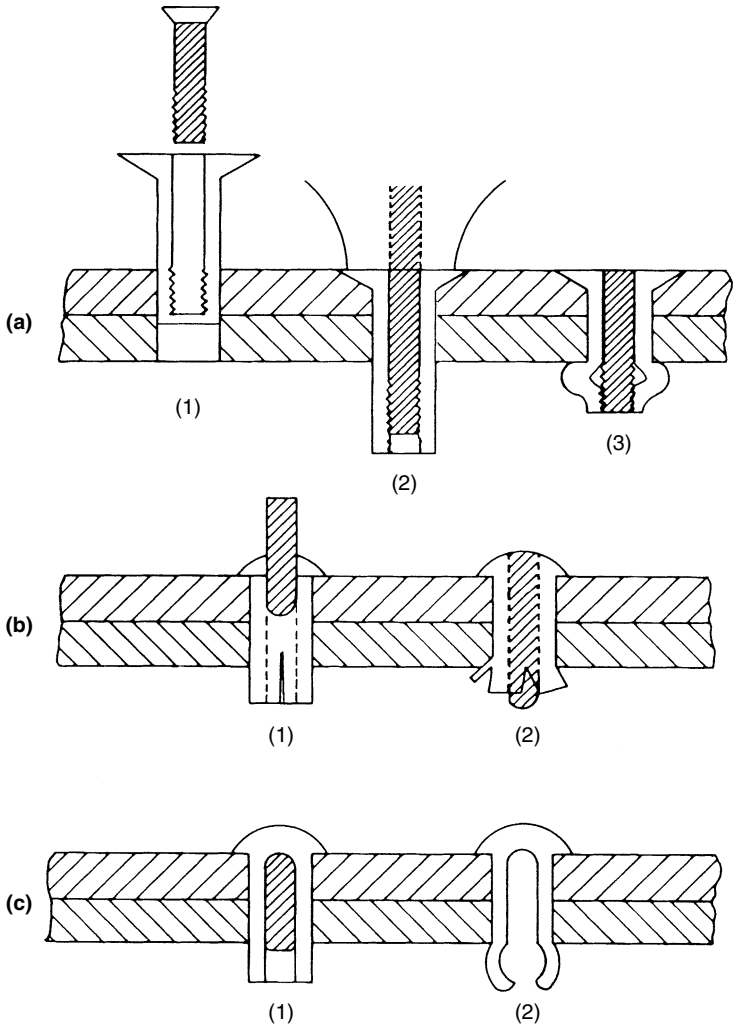

Figure 3.26 Schematic illustration showing the operation of other types of rivets suitable for use in "blind" application including (a) rivnuts, (b) Southco blind rivets, and (c) DuPont explosive rivets. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.20, page 87, with permission of Elsevier Science, Burlington, MA.)

shank expands to set the rivet, as shown in Figure 3.26c. Some special fasteners that are capable of self-setting or self-upsetting by employing a metallurgical solid-phase transformation are described in Subsection 3.4.4.

So-called "pop-rivets" are a subgroup of blind fasteners that were developed in England many years ago and have been widely used there ever since. Application in the United States was slow to develop but has grown in recent years. The two design types are "break-head mandrel" and "break-stem mandrel." Both consist of a hollow rivet

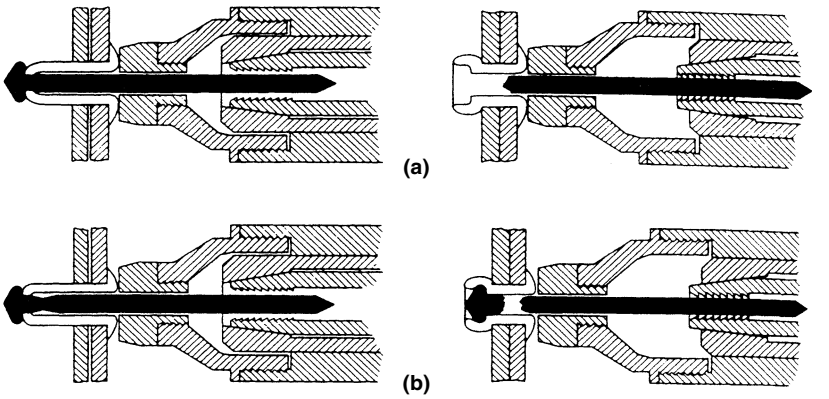

Figure 3.27 Break-head mandrel (a) and break-stem mandrel (b) pop-rivets. (Reprinted from *Handbook of Fastening and Joining of Metal Parts*, V. Laughner and A. Hargan, Figure 5.28, page 216, McGraw-Hill Publishing, New York, NY, 1956, with permission.)

and a solid mandrel. A special tool pulls the mandrel into the rivet, upsetting it and creating a clinching or locking force. A recess or undercut causes either the head or the stem to break off with a characteristic "pop," hence the name. A telltale tipoff that break-head mandrel pop-rivets have been used in assembly is the presence of a small scar on the crown of the head. A popular application of such rivets is in the assembly of sheet-metal skins on campers, school buses, curbside delivery vans, and other light-weight vehicles. Typical designs are shown in Figure 3.27.

Standards for blind rivets have been established by the Industrial Fasteners Institute (IFI), under IFI Standards 114, 116, 117, 119, 123, and 126, as well as by the Department of Defense (in Military Standards) and by the National Aerospace Standards Committee (under NAS standards).

In order for a blind rivet to work, the material used in the pull or drive pin must be stronger than that used in the rivet body, which must be relatively ductile to permit expansion without damage. Thus, multiple materials are used in individual systems. Rivet bodies are often made from aluminum alloys, low carbon steels, stainless steels, or some brasses and nickel–copper alloys. The drive pin or pull portion is made of a higher-strength material, selected to be electro-chemically compatible with the rivet body and the material(s) being fastened. Carbon and low alloy steels, stainless steels, and special heat-resistant alloys have been used. For aerospace, titanium and titanium alloys have also been used for both rivet bodies and drive pins.

3.4.4 Self-Setting or Self-Upsetting Fasteners

There is a special group of unthreaded fasteners that are akin to rivets, except that the foot of the fastener that locks it into a joint element is formed without requiring setting or upsetting from an external source. These *self-setting* and *self-upsetting fasteners* create either a locking action without having to form a foot, or create a foot that may not

only lock the fastener in place but may produce a clamping force (albeit a small one) on the joint as well, by having the material comprising all or part of the fastener undergo a reversible solid-state phase transformation. Materials that exhibit such a reversible solid-state phase transformation are said to have a "shape-memory effect," making them shape-memory alloys or SMAs. A shape-memory effect comes about from a diffusionless, athermal, or martensitic phase transformation. Such transformations typically result in a fairly significant volume change. One such material is Nitinol,[13] an alloy of 55Ni-45Ti developed by the Naval Ordnance Laboratory and used in making fasteners for specialized applications.

When a fastener such as a tubular rivet is fabricated from Nitinol, it can have the upset or locking feature formed in at the same time it is in the higher-temperature "austenite-like" phase. By subsequently deforming the fastener shank at a lower temperature (when the fastener material is in its martensitic state to remove the fabricated-in upset during the fastener's manufacture) the fastener can be made ready for insertion into a prepared hole. As long as the fastener is kept at a temperature below the point where the shape-memory transformation to the "austenite-like" phase occurs, no change takes place. Once the fastener is inserted into the pre-prepared hole (with very little force being required) and allowed to heat up to room temperature, the transformation to the upset state occurs and the fastener locks in place, locking the joint elements together at the same time. Figure 3.28 schematically illustrates a design developed and tested at Rensselaer Polytechnic Institute in an automated fastening technology research program in 1989–1992.

Although these fasteners seem to have potential, they have seen only limited application because of other problems, such as poor corrosion resistance, incompatibility with corrosion-prone joint materials, and cost.

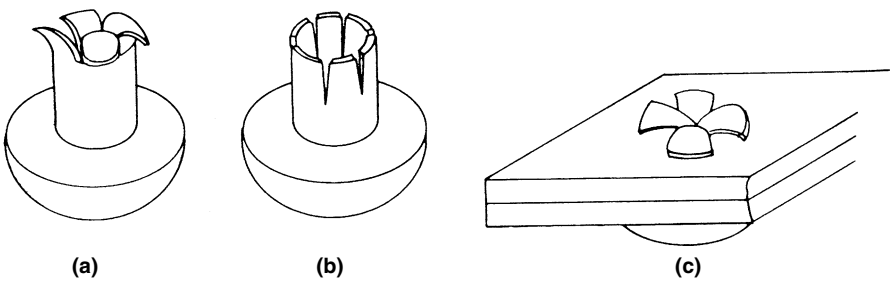

Figure 3.28 Schematic illustration of a self-upsetting rivet made from a shape-memory alloy. The pre-formed-in shape in the higher-temperature "austenitic" phase is shown in (a), the modified shape in the lower-temperature "martensitic" phase is shown in (b), and the restored shape-memory shape is shown in (c) once the installed rivet warms back up into the "austenitic" phase. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.29, page 96, with permission of Elsevier Science, Burlington, MA.)

[13] "Nitinol" is actually an acronym for Ni-Ti-Naval Ordnance Laboratory.

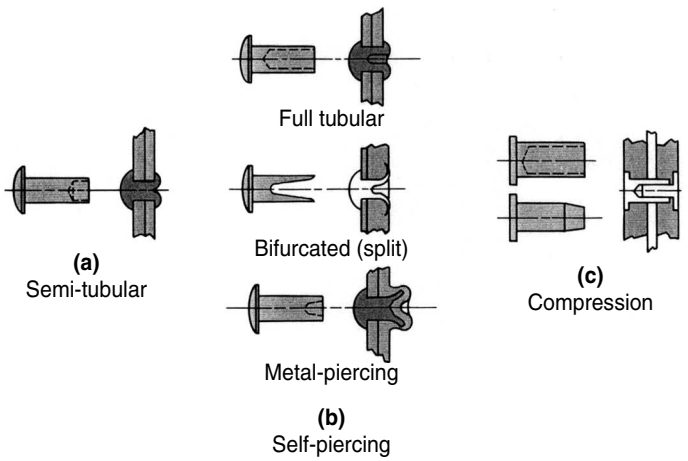

Figure 3.29 Schematic illustrations of a few types of "self-piercing" rivets being installed in a joint are shown in (b). A one-piece upsetting tubular rivet is shown in (a), while a two-piece lock-rivet, or high-shear rivet, is shown in (c). (Reprinted from *Fundamentals of Machine Component Design*, R.C. Juvinall and K.M. Marshek, John Wiley & Sons, Inc., New York, NY, 1991, with permission.)

Another fastener type "self-sets" by simply pressing through relatively soft joint elements, making a hole to accommodate itself as it goes, and locking itself in place by the elastic recovery that accompanies full insertion. Such "self-piercing" rivets are shown schematically in Figure 3.29.

3.4.5 Pins, Pegs, and Nails

The oldest mechanical fastener (if one ignores lashings, to be discussed briefly in Subsection 3.6.4) is undoubtedly the *pin*. A pin is a machine element or fastening component or device that secures the positions of two or more parts relative to one another in a structure or assembly by passing through holes in those parts. Pins usually remain fixed in place by the friction caused by interference between the pin's surface and the material surrounding it in the part(s) into which it is inserted. This friction force is the result of the microscopic asperities on the surface of the pin (whatever material it is made of) and on the surface of the hole surrounding the pin (whatever material those parts are made of). Any squeezing force from the material into which the pin is installed causes the friction force to be higher. A squeezing force results from the material surrounding the pin pushing back on the pin in its attempt to recover the elastic portion of the deformation forced upon it by insertion of the pin. However, there are also pins that must be held in place axially to allow intentional radial motion (e.g., rotation of one part relative to another or, at least, to the pin). Pins often have neither heads nor feet and, consequently, are incapable of developing any clamping force. They are intended to operate in shear by bearing against the material into which they are inserted. As a group, pins are cost effective because of their simplicity of design, ease of installation, and ease of removal for intentional disassembly.

Originally, pins were simple, solid, straight cylinders (with the possible exception of wooden pegs when they first appeared tens of thousands of years ago, which were commonly tapered). Today there are more elaborate designs for ever-widening applications. Like rivets, pins can and do act as pivot shafts to allow a part to move, usually in rotation.

Pins come in many types, with two major subtypes, pegs and nails, to be described later. Figures 3.30 and 3.31 show what are generally recognized as pins, and here are more detailed descriptions:

- *Straight cylindrical pins* are headless cylinders, with or without chamfered ends, used for transmitting torque in round shafts.
- *Dowel pins* are often hardened headless cylinders used in machine and tooling fabrications for fixing the position of parts of the machine or parts inserted into the tooling (including jigs and fixtures).
- *Tapered pins* are headless tapered rounds used in drilled and/or reamed (often taper-reamed) holes for fixing position or transmitting torque. The taper helps ensure that interference is established through a wedging action.

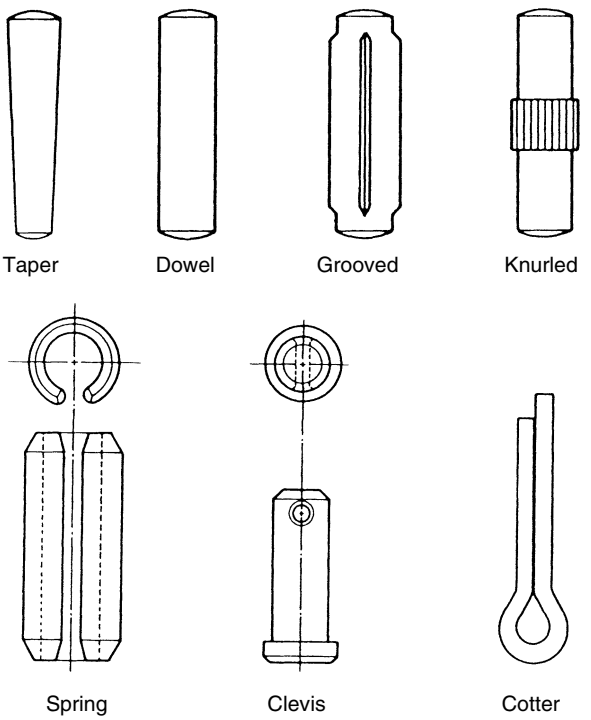

Figure 3.30 Schematic illustration of various major pin designs. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.22, page 89, with permission of Elsevier Science, Burlington, MA.)

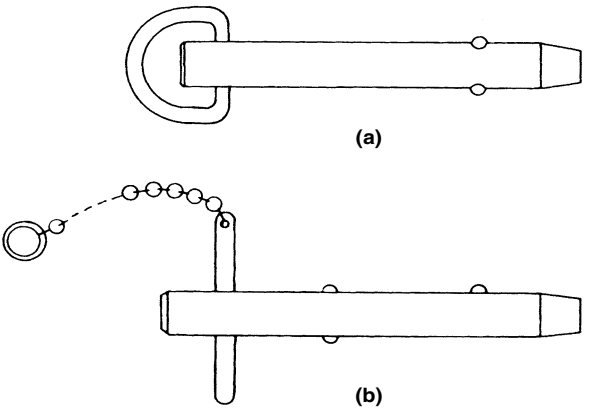

Figure 3.31 Schematic illustration of some "quick-release" pin designs. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.23, page 89, with permission of Elsevier Science, Burlington, MA.)

- *Clevis pins* require the use of a second, smaller pin (often a cotter pin) placed through a hole drilled diametrically through the body of the headless end of the clevis pin in order to keep it from accidentally withdrawing.
- *Cotter pins* are headed pins held in place by bending outward the projecting portions or prongs of a split body at the headless end, thereby preventing unwanted withdrawal.
- *Spring pins* are held in place by the elastic spring action of the body created by an axial slot or a spiral-wound design. Slotted tubular pins and spirally coiled pins are the two predominant types.
- *Grooved pins* typically have three equally spaced, parallel axial grooves impressed longitudinally onto the exterior of the pin body. These grooves ensure positive radial locking in a hole by forcing some of the material of the part into the grooves by plastic deformation.
- *Knurled pins* have a cross-textured ("knurled") surface for use in soft metal diecastings or polymers to prevent unwanted withdrawal.
- *Quick-release pins* are used for temporarily fixing the position of parts during assembly or to facilitate disassembly. These pins often use spring-loaded lock-balls located in the pin body in the region that projects through the part being fastened.
- *Barbed pins* are usually headed types with projections along the pin body to facilitate locking in soft materials such as plastics or wood.

Pins are generally manufactured to an ANSI Standard—B18.8.2 for the straight, dowel, taper, grooved, and spring types, and B18.8.1 for the clevis and cotter types. They are fabricated from many materials, depending on the design type and intended use. Most, however, are fabricated from various cold-drawn low or medium carbon or low alloy steels and, as mentioned, some are hardened for wear resistance. Other materials typically used include various stainless steels (especially 400-series grades), brasses,

bronzes, and beryllium–copper. Special light-duty pins for use with plastics, ceramics, or glasses can be fabricated from other, softer materials.

Two special and particularly important subtypes of pins are pegs and nails. *Pegs* are made of wood and are intended for joining wood or occasionally stone. Pegs can be of any cross-sectional shape, but round and square are most common, with round pegs intended for placement into round holes and square pegs intended for placement into square holes. In either case, the pegs are tapered along their length and are almost always headless. They are driven into the properly sized and shaped hole by hammering or occasionally pressing. The natural ability of wood to easily and elastically compress allows pegs to grip and hold themselves (and the parts into which they are inserted) in place. The frictional force that holds pegs in place can be high because the wood of which the peg is made and the wood or stone parts into which they are driven is rough, and because wood tries to elastically recover once driven into place, applying a considerable back force. Sometimes wood pegs are driven into place after they have been soaked in water, to soften them to allow them to be driven deeper to develop more back force.

Nails (and their bigger cousins, spikes) may be the most common of all mechanical fasteners, and are absolutely the most common fastener used to assemble structures constructed from wood. They are always driven into wood or other soft materials, like some plastics, and so must have sufficient strength to tolerate the driving force along their length. A nail is pointed at its tip (i.e., opposite its head, where the driving force is applied) to facilitate penetration of the wood (or other material) without splitting. Standard types include (1) standard wire nails or brads; (2) annular grooved nails; (3) cement-coated nails; (4) spirally grooved nails; (5) zinc-coated and galvanized nails; (6) barbed nails; and (7) chemically etched nails. Several of these types have the surface of the shank of the nail processed or treated to improve its withdrawal resistance. Like their generic "parents" (pins), nails are intended to operate in shear by bearing. However, by using the aforementioned gripping surfaces as well as by driving them at an angle (as opposed to perpendicularly) to the surface of the materials they are intended to fasten (i.e., "toe-nailing" or "toeing"), they can resist tension forces.

Nails are virtually always fabricated from metal, often low or medium carbon steels, but also stainless steel or zinc-galvanized steel for corrosion resistance, aluminum alloys, copper, or copper alloys (like brasses or bronzes or cupro-nickel).

The spacing of nails from one another and from edges is not standardized but is still important. It is largely experiential and is always dependent on the hardness of the wood into which they are being driven. Every nail, by type and size, has an allowable lateral loading value, a minimum penetration depth to achieve maximum lateral loading, as well as a withdrawal force. These are given by Parmley (1989).

Figures 3.32 and 3.33 schematically illustrate the most common types of nails and the sizes of so-called "common nails," respectively.

3.4.6 Eyelets and Grommets

Eyelets and *grommets* may not be well known by these names, but they are recognized as commonly used unthreaded fasteners in certain soft, flexible, or pliable materials like

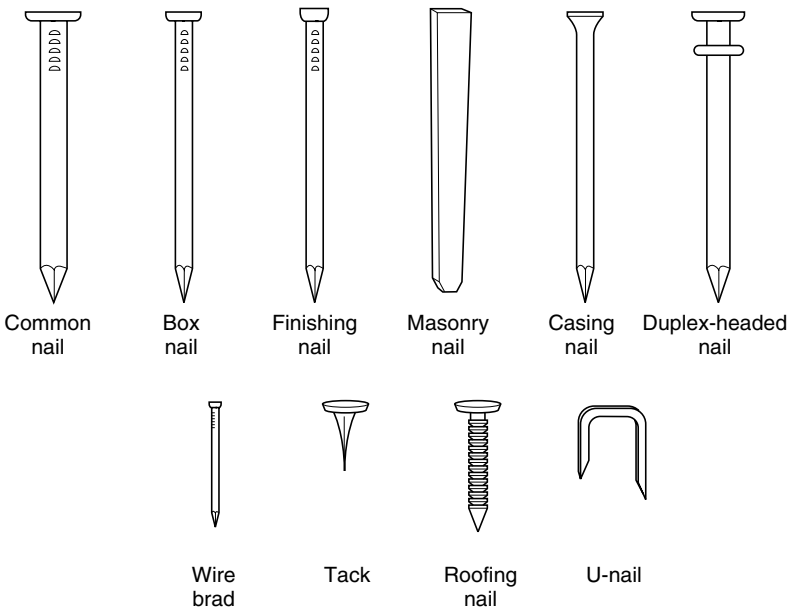

Figure 3.32 Schematic illustration of various common types of nails, including, from left to right, common nail, box nail, finishing nail, masonry nail, casing nail, duplex-headed nail, wire brad, tack, roofing nail, and U-nail.

textiles, leather, and composites. Eyelets are certainly known from their use in shoes that are tied by laces. Grommets are best known by the common name for one form (i.e., "snaps"), used as closures on garments.

For some applications, eyelets and grommets are trouble-free and economical fasteners. They can be assembled very rapidly using special machines that punch holes and insert and set the eyelets and grommets simultaneously. Typically, eyelets and grommets are used in relatively soft materials that are prone to tearing and other damage from other fasteners. Such materials include cloth, leather, rubber, and (more recently) certain polymer-matrix composites. Eyelets are used where shearing stresses and pressure tightness are not important considerations. When this is the case, they can be used in place of rivets, offering savings in weight and cost. An eyelet provides a hole for fastening with an edge protected against damage by tearing, for example. Eyelets can be used with hooks, laces, and ropes, or to provide passage for wires to prevent wear or abrasive damage to the wire or the wire's insulation.

The grommet consists of a mating set of male and female units for actually joining two parts or materials by inserting one unit into the other, often with an elastic snapping action, hence the common name "snaps." As mentioned above, a common use of grommets is in the closures on leather and cloth garments like leather jackets. Eyelets and grommets are usually fabricated from soft, highly deformable materials that can be set easily, such as copper, brass, aluminum, zinc, low carbon steel, and nickel silver. There are no particular standards for these fasteners, but there are many

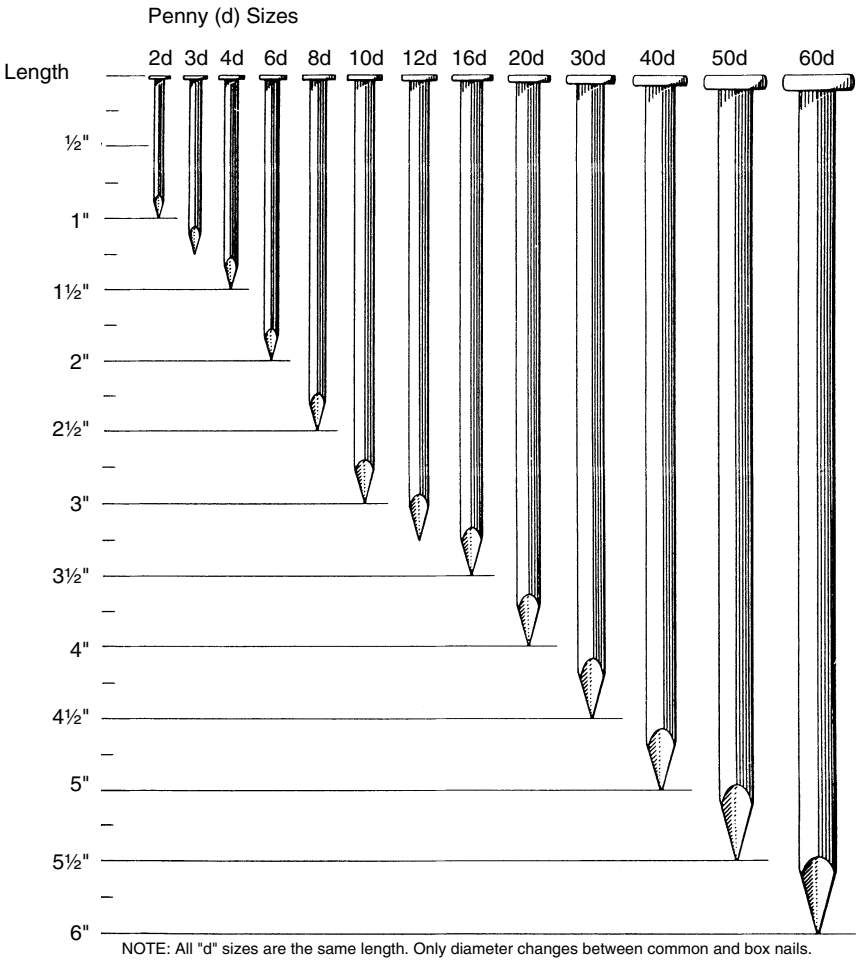

Figure 3.33 Schematic illustration showing the relative sizes of so-called ''common nails.'' (Reprinted from *Estimating for Residential Construction*, Van Orman, Delmar Publishers, Inc., now Thomson Learning, Belmont, CA, with permission.)

styles and hundreds of sizes. A few of the more important styles are shown in Figure 3.34. Joining of these fasteners is the result of friction, with or without some elastic deformation and at least partial recovery.

3.4.7 Retaining Rings and Clips

Shoulders (i.e., larger diameter portions) are usually used on shafts or on the interior of bored parts (e.g., counter-bored recesses) to accurately position and/or retain assembled parts to prevent axial motion or play. It is often advantageous to use *retaining rings* or *clips* (or ''snap-rings'' or ''snap-clips'') as substitutes for these machined, integral

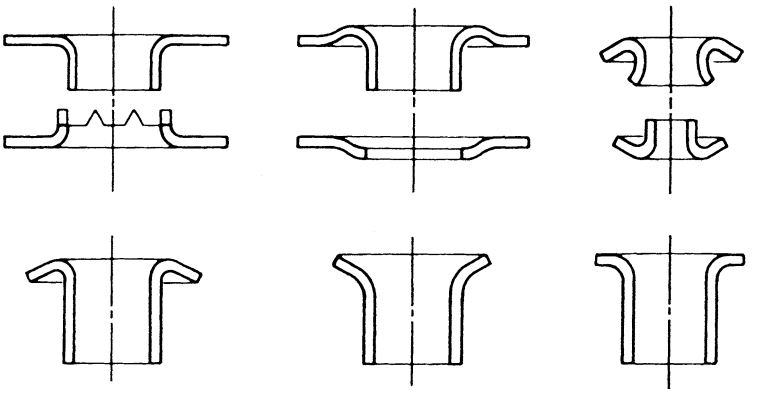

Figure 3.34 Schematic illustration of (a) eyelets and (b) grommets, showing how various types of grommets are assembled. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.24, page 91, with permission of Elsevier Science, Burlington, MA.)

details. Such rings or clips can be used to axially position parts on shafts or in bored housings with great precision, often saving a great deal of money on machining. They also facilitate intentional disassembly for maintenance or repair. All retaining rings and clips depend on elasticity in both their design and material of construction to function, in that they are either sprung or snapped into position or apply a spring load to the assembly.

Retaining rings and clips come in many varieties, all within three basic types based on the purpose to be fulfilled, as follows:

- *Axially and radially assembled groove rings or clips* are split or crescent-shaped rings, respectively, that require a groove in the part on which they are being used to properly perform their function of locating and retaining part position.
- *Endplay take-up rings or clips* are bowed or beveled in the plane of the ring or clip to allow flexing and provide a spring force to resist unwanted play or "mechanical slop."
- *Self-locking rings or clips* have various prongs or protrusions or other features to permit the ring or clip to lock into position without the need for a groove.

Retaining rings and clips are fabricated in either stamped sheet metal or as spiral-wound wires or strips. Because they depend on the ability to deform elastically during assembly or intentional disassembly to perform their intended function, they are fabricated from materials that have inherently good spring properties (i.e., high proportional limit and/or yield strength and reasonable modulus of elasticity, as well as good resilience). These materials include medium to high (0.6–1.0%) carbon, silicon-containing spring steels, precipitation-hardening stainless steels (e.g., 15-5 and 17.4 PH), and beryllium–copper alloys. Since the strengths and elastic moduli of materials from which retaining rings and clips are fabricated are high, the thrust they can develop is high. Consequently, they can be used to replace nuts, machined or forged shoulders, collars, cotter pins, or other positioning or thrust devices.

Specific advantages of retaining rings and clips are that (1) they allow quicker intentional disassembly of parts; (2) they may be accurately positioned without marring; (3) they reduce machining through the use of an auxiliary part; (4) assembly design is simplified; (5) size and weight are reduced compared to heavier nuts; and (6) looseness or endplay from accumulated tolerances during manufacture or from wear in service is eliminated.

Retaining rings and clips are generally manufactured to industrial standards such as those of the Industrial Retaining Ring Company, but they are also covered by ANSI Standards B27.6 and B27.7. Some typical retaining ring and clip designs and the ways they are used are shown in Figure 3.35.

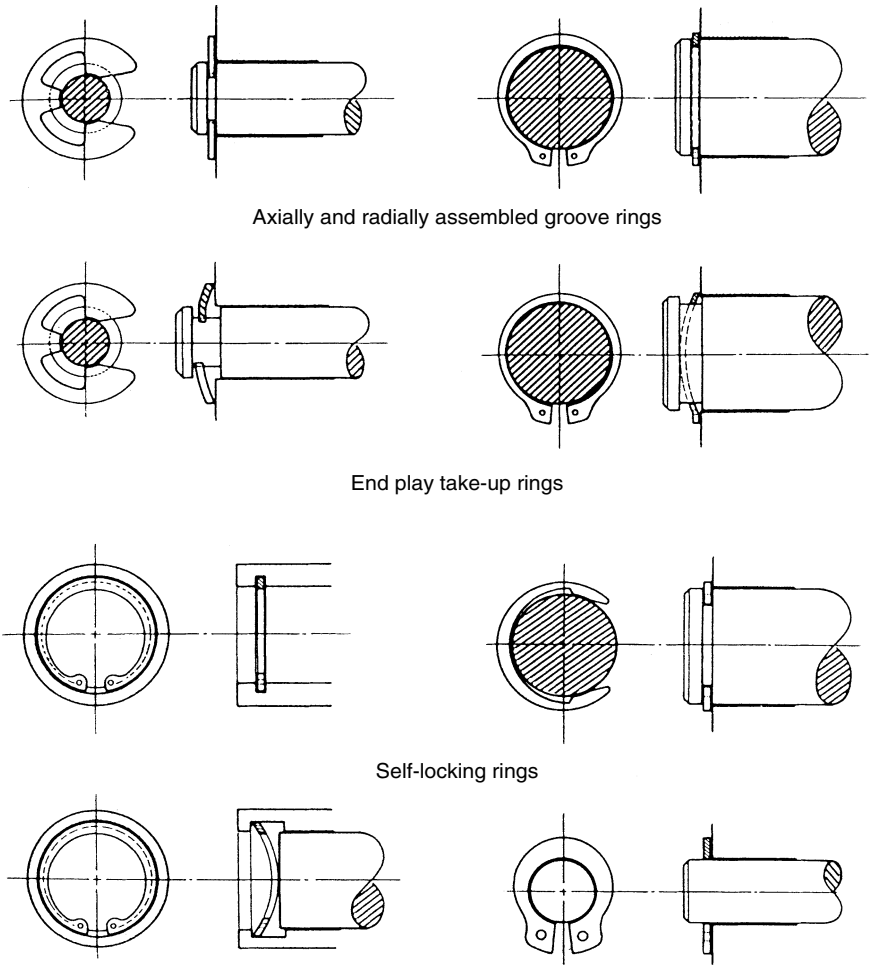

Figure 3.35 Major types of retaining ring or clip designs. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.25, page 93, with permission of Elsevier Science, Burlington, MA.)

3.4.8 Keys and Keyways

Keys are solid pieces of various shapes used in combination with mating, similarly shaped slots called *keyways,* to fasten two parts (usually to prevent relative circumferential or rotational motion to transmit torque). These mating fasteners may or may not prevent relative longitudinal or axial motion, depending on the type of key and keyway used. Figure 3.36 schematically illustrates how keys are used with keyways, while Figure 3.37 schematically illustrates a variety of different key–keyway types. The designs and materials used for keys and for keyways or key seats are covered by ANSI B17.2 and B17.7. Materials used in keys are usually cold-finished steels, although other materials may be used for compatibility with the parts being fastened.

Another approach to preventing relative circumferential motion is to use raised ridges regularly spaced around a shaft, running longitudinally (or axially) along the shaft. Commonly called "splines," they are an integral design feature rather than a fastener (see Subsection 3.5.2).

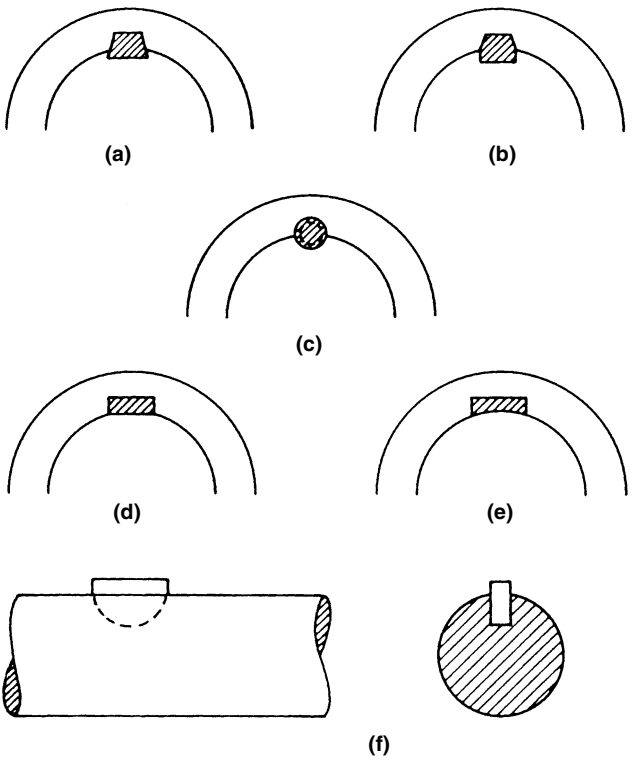

Figure 3.36 Schematic illustration showing the function of keys in keyways for (a) dovetail keys, (b) beveled keys, (c) round-tapered keys, (d) flat-saddle keys, (e) hollow-saddle keys, and (f) Woodruff keys. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.26, page 94, with permission of Elsevier Science, Burlington, MA.)

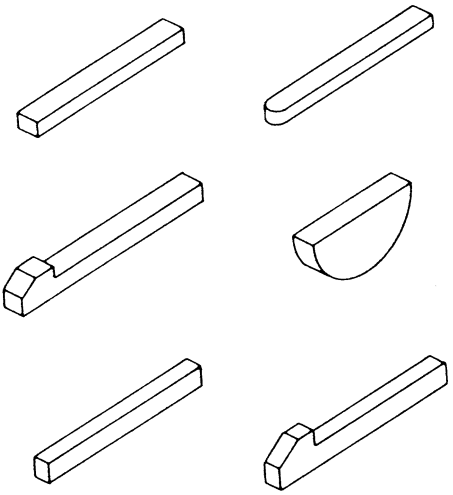

Figure 3.37 Schematic illustration of various keys. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.27, page 94, with permission of Elsevier Science, Burlington, MA.)

3.4.9 Washers and Lock-Washers

Perhaps the simplest and least appreciated unthreaded fastener of all is the washer. *Washers* are simple, usually flat (or nearly flat), usually circular secondary fasteners used with bolts, screws, and nuts, usually in tension-loaded joints. They serve one or more of several purposes, which include (1) to spread the load applied by the fastener head and/or nut, especially with soft, deformable materials (e.g., soft metals, polymers, wood, or fabrics) or damage-prone materials (e.g., brittle ceramics, glasses, or reinforced composites, especially those with polymeric or carbonaceous matrices); (2) to obtain additional bolt tension or preload and clamping force on the joint by acting as a shim or spacer; (3) to take up or compensate for relaxing bolt tension or preload or looseness in the joint (e.g., when using spring washers); or (4) to help prevent loosening (e.g., when using lock-washers). Washers can be employed under the head of a fastener, under the nut, or under both. These various uses are schematically illustrated in Figure 3.38.

Among the variety of washer designs are plain, cylindrical curved, conical or Belleville, slotted, spring, or spring-locking types. One important class of washers is the "lock-washer." As the name implies, these washers have design features that help the washer lock into place. They also apply a spring action (or back force against the structure and/or the nut), and they take up mechanical "slop" to prevent loosening. There are helical-spring, internal-tooth, external-tooth, internal–external-tooth, beveled, and Belleville varieties of lock-washers.

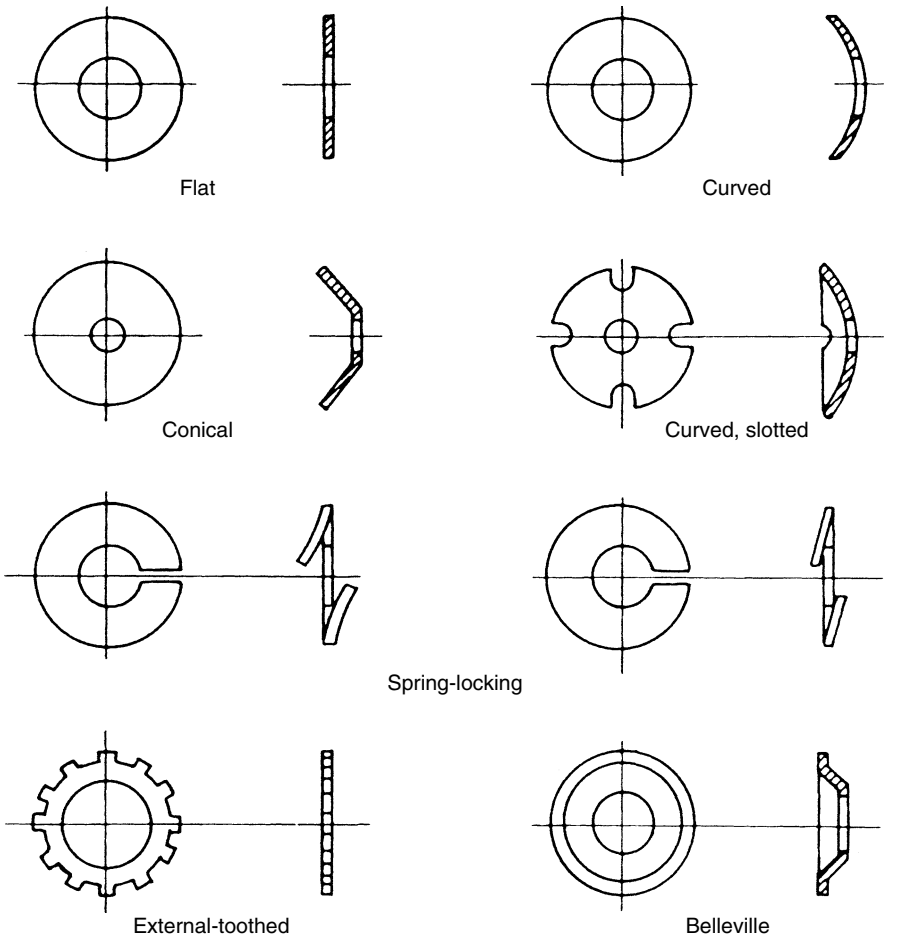

Figure 3.38 Schematic illustration of various washer designs. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.28, page 95, with permission of Elsevier Science, Burlington, MA.)

Washers can be made from almost any material, depending on the intended function of the washer and the application of the joint. For most applications, carbon steel, corrosion-resistant steel (most often 302 or 305 austenitic stainless steels), aluminum–zinc, phosphor bronze, silicon bronze, and K-Monel are used, especially for spring type lock-washers. Soft, fibrous materials or electrically insulating materials may be used for special purposes, such as vibration damping, fluid sealing (i.e., gasketing), or electrically insulating the fastener from the joint element(s) either to allow assembly function or prevent unwanted galvanic corrosion. Lock-washer designs and materials are covered by ANSI B18.21.1, while bevel washer designs and materials (for use on inclined surfaces) are covered by ANSI B27.4.

3.5 INTEGRAL MECHANICAL ATTACHMENTS

3.5.1 General Description of Integral Mechanical Attachments

Even older than the use of mechanical fasteners for joining materials and structures is the use of integral mechanical attachments. The reason for this is that, in their simplest and surely oldest form, such attachments can be found to naturally occur in some materials. Forks in sticks of wood (i.e., branches) and naturally shaped stones that are able to nest and interlock with other stones with naturally occurring complementary shapes are good examples, as shown in Figures 1.1 and 3.39. The next logical advancement was the creation of shapes that allow interlocking as part of the design and subsequent fabrication of objects to be assembled, with stones that are cut to fit together tightly (and even interlock) being good examples. The wondrous and awe-inspiring stone temples of the Mayans, the great pyramids of the ancient Egyptians, and the great walls and arches of the Romans are all examples of integral mechanical attachment. More modern examples can be found in the design of a wide variety of products from cell phones to Celicas.[14]

Figure 3.39 Photograph of an old stone bridge during its construction showing the nesting and interlocking of naturally shaped and cut stones. (Courtesy of Bechtel Corporation, San Francisco, CA, with permission.)

[14] The Celica is a popular automobile manufactured by the Toyota Motor Company.

Another form of such integral attachments is that group that are formed into or otherwise processed into parts to cause their materials to interfere and their parts to interlock. Examples include crimped soft-metal terminal connectors on electrical wires. A terminal connector locks onto twisted fine wires by having the soft metal in the connector forced into intimate contact with, surround, and interlock into the geometric shape of the wire bundle, on macroscopic and microscopic levels.

As a group, all integral mechanical attachments and interlocks share the common advantage of ease of use from a logistics standpoint. Since the features needed to cause interlocking, interference, and joining are integral to the parts being joined, one or more of the tasks of finding and handling fasteners, preparing needed holes or slots or grooves, and using tools to accomplish fastener installation to accomplish assembly are eliminated. Basically, if the parts to be assembled are already there, assembly can be made to occur. Furthermore, in many cases, assembly can be automated much more simply than if fasteners are required. Pushing or sliding two parts together using low forces is much simpler for a robot to accomplish, for example, than to place a nut on a bolt so that the threads engage (without cross-threading!) and then tighten the nut and bolt assembly.

This section looks at this too-often-ignored approach to mechanical joining.

3.5.2 A Suggested Classification Scheme for Integral Mechanical Attachments

If one considers all the ways that integral mechanical attachments actually operate, using naturally occurring, designed-in, or processed-in features, it becomes apparent that there are three fundamental classes of such attachments: (1) rigid interlocks, (2) elastic interlocks, and (3) plastic interlocks (Messler and Genc, 1998). Knowing this allows one to understand how a particular feature operates to cause joining, in what materials such a feature can likely be produced, and how such a feature can be expected to perform in terms of load-carrying capability and reliability from the standpoint of permanence.

Rigid interlocks are those that have a naturally occurring or designed-in and prefabricated geometry. They all consist of two opposing complementary shapes that can be caused to engage with some simple motion in some direction. They interlock once engaged and successfully carry a load in one or more directions different from the direction in which they were caused to engage. In being rigid, the interlocking features are expected to operate well within the elastic limit of the material(s) in which they exist or were created. Exceeding the elastic limit would cause the interlock to fail by causing the material(s) to fail in either a plastic or brittle fashion. This characteristic of rigid interlocks suggests that they are best used in materials that do not exhibit much plasticity (if any) or in parts that should not ever deform if they are to function. Candidate materials include wood, ceramics (including stone, brick, cement, and concrete), brittle or simply very high-strength metals (e.g., cast iron or quenched and tempered tool steels), and rigid polymers (typified by many thermosetting types) or reinforced polymer-matrix composites.

Some examples of rigid interlocks (to be expanded upon in Subsection 3.5.3) are (1) dovetails, tongues-and-grooves, and mortis-and-tenons in wood; (2) protrusions and notches or various tongues-and-grooves in ceramics such as cement or concrete; and (3) dovetails-and-grooves or Ts-and-slots in cast iron and tool steel machine ways.

Elastic interlocks are those that have a designed-in and prefabricated feature (or sometimes a naturally occurring feature) that engages with a rigid feature in an opposing and mating part to cause interlocking of the two parts. The critical characteristic of these features is that at least one (and usually only one) of the opposing features is designed to elastically deflect. Once it fully engages with its rigid mating feature, it elastically recovers, at least partially, to cause interference, interlocking, and joining. That same feature might be caused to elastically deflect in the opposite direction to permit disassembly. Being designed to intentionally allow elastic deflection in some direction (but not all directions!), these features provide the most effective joining when they are caused to resist applied service loads in directions orthogonal to the insertion direction as well as the release or so-called "retention" direction. Loads in the insertion or retention direction, which are along the same Cartesian axis but with opposite senses, can cause disengagement of the elastic portion from the rigid portion of the locking pair unless some special precautions are taken to prevent this.

Candidate materials for elastic interlocks are those materials that exhibit good elasticity, but not unacceptably low moduli, as such materials would deflect too easily. The best examples are the more rigid polymers (not elastomers); thermoplastic and thermosetting types are acceptable, but thermoplastic types are far more popular due to the ease with which they can be fabricated into parts by molding. Other good candidates are metals, with many examples appearing in sheet-metal assembly. There are even examples in wood but applications tend to be limited, mostly because wood tends to dry out and lose its elasticity over time.

Some examples of elastic interlock features (to be expanded upon in Subsection 3.5.4) are (1) snap-fits in plastics and metals; (2) thermal interference shrink fits; and (3) elastic interference press-fits in metals.

Plastic interlocks are those that are processed into parts once they are brought into contact in the arrangement and orientation in which they are to remain in an assembly or structure. Interlocking features are created at interfaces between abutting parts by plastically deforming one or both materials to cause interlocking protuberances and/or recesses where one or the other does not already exist. In some methods of producing such interlocks (e.g., crimps), one material is caused to form down onto, around, and into recesses among non-deforming mating parts (e.g., a twisted bundle of fine wires). Once formed, such plastic interlocks tend to be quite strong, often because there has been some strain-induced hardening of the material during deformation. The force needed to cause parts to separate must give rise to stresses that exceed the yield strength of at least one of the mating parts, damaging that part in the process.

Since plastic deformation is essential to this type of assembly, these features are restricted to plastically deformable materials, such as soft, ductile, or malleable metals and polymers (especially, but not only, thermoplastics). Examples (to be expanded upon in Subsection 3.5.5) are (1) crimps, (2) hems, (3) stakes, and (4) certain plastic interference press-fits.

3.5.3 Rigid Integral Mechanical Interlocks

As described in the preceding subsection, rigid integral mechanical interlocks must be designed and pre-fabricated into mating parts (unless they happen to occur naturally, which is rare!). They are best used with materials that do not exhibit much elasticity or plasticity, or with parts that must not deform to remain functional. Hence, it should come as no surprise that rigid interlocks are found in (and are useful for) parts to be assembled that are made of wood; stone, cement, or some other ceramic; glass; or hard and brittle or high strength metals (e.g., cast-iron manhole covers). Let us consider some important examples in reverse order, starting with metals.

Figure 3.40 schematically illustrates some common rigid integral interlock features used with metal parts to allow joining of one part to another. Examples include,

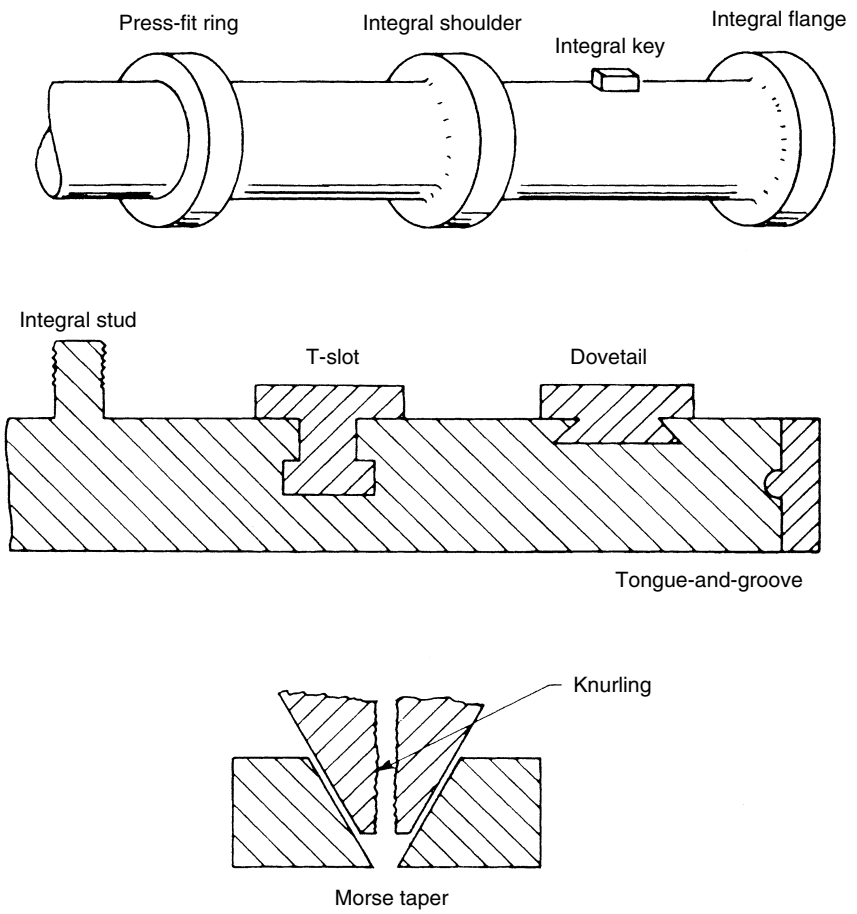

Figure 3.40 Schematic illustration of rigid interlock features used with metals. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.31, page 100, with permission of Elsevier Science, Burlington, MA.)

but are not limited to (1) integral flanges and (2) shoulders (used to make connections to shafts or pipes, end-to-end or concentrically); (3) integral keys or (4) bosses (to lock concentric parts together); (5) T-slots and Ts and (6) dovetail grooves and dovetails (to join parts to allow relative motion along the slots or grooves, but resist shear and tensile forces in orthogonal directions); (7) integral threaded or unthreaded studs (to allow positioning and mounting of another part); and (8) Morse tapers (used to wedge one part up against another, as a tensile coupon in a tensile testing machine's grips).

Flanges and shoulders, integral bosses, and wedge-stops (as in a stopper in a bottle) can also be found in glass parts, along with molded-in male and female threads. For integral threads such as those found on screw-top jars,[15] the threads are coarse, large pitch, and rounded at their crowns and roots to minimize adverse stress concentration.

Various rigid integral interlocks are also used in construction joints for stone, brick, cement, and concrete, with examples shown schematically in Figure 3.41.

Finally, a number of well known rigid integral interlocks and a couple of novel integral features with novel fastening parts are found in wood construction in old barns, old and new homes, old wooden bridges, wooden ships, and fine wood furniture. These include (1) various dadoes such as through, blind, dovetail, and rabbet; (2) various single and multiple tongue-and-groove joints; (3) mortise-and-tenon joints (of which there are through, blind, and "haunched" types); and (4) doweled and "biscuited" joints. These are all shown schematically in Figure 3.42.

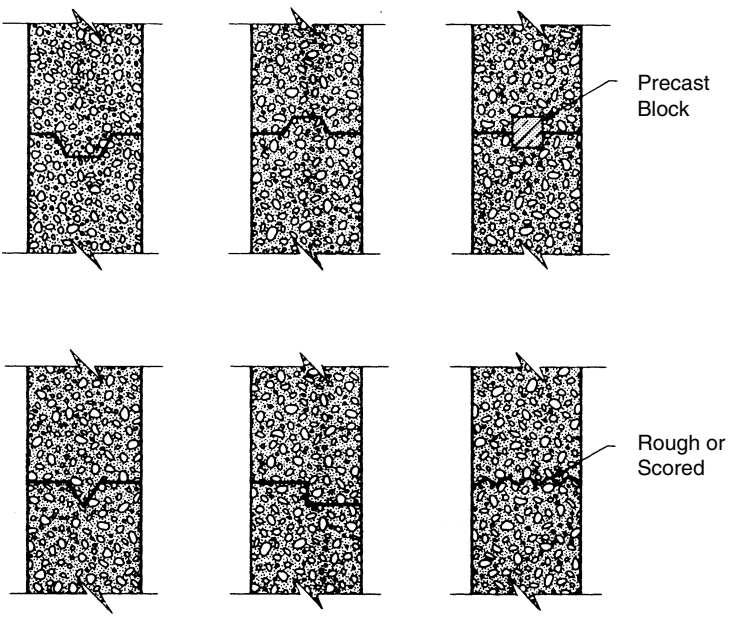

Figure 3.41 Schematic illustration of rigid interlock features used in joining poured cement or concrete, pre-cast cement or concrete blocks, or molded/fired clay or other ceramic bricks.

[15] Screw-top glass jars usually employ integrally threaded metal caps or covers.

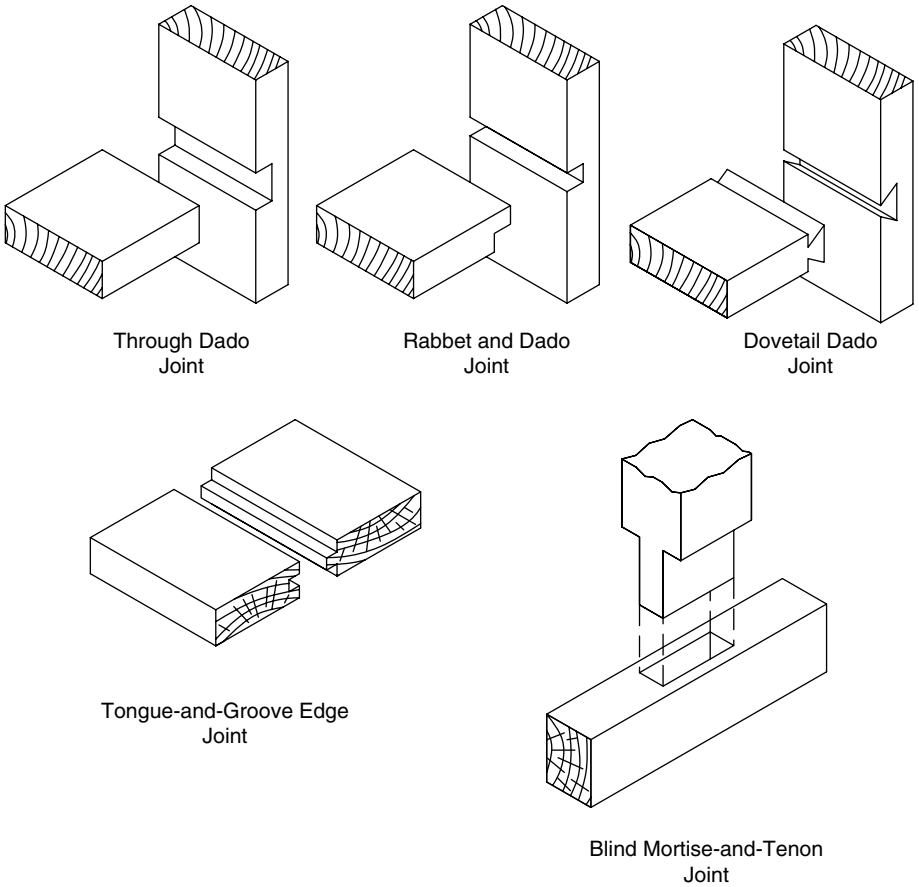

Figure 3.42 Schematic illustration of important rigid interlock features used in assembly of wood parts, including, from left to right, through dado joint, rabbet and dado joint, dovetail dado joint, tongue-and-groove joint, and blind mortise-and-tenon joint.

3.5.4 Elastic (Snap-Fit) Integral Mechanical Interlocks

An increasingly popular form of mechanical joining is "snap-fit fastening." This is actually a misnomer because fasteners are not usually involved[16]—elastic integral mechanical interlocks are. As described in Subsection 3.5.2, elastic integral mechanical interlocks function by having one feature on one part in a mating pair be designed so

[16] There are, in fact, actual "snap-fit fasteners." These are usually headed clevis-like rivets or pins that are inserted into pre-prepared holes by squeezing some elastically deformable feature until the fastener is fully in place, and then releasing the squeezing force to allow the fastener to elastically recover (at least partially).

that it can and does elastically deflect when it comes into contact with a rigid feature on the mating part. Once deflection and insertion reach a certain point, the designs of the deflecting and rigid features are such that the deflecting feature clears the rigid feature and is able to elastically recover at least partially, if not completely. When this recovery takes place, there is usually a distinctive "snap" that can be heard and felt. This permits built-in quality assurance that a successful engagement and locking has occurred. In this recovered position, the geometry of the details on the two mating features act to lock the two parts together. Thus, the two features operate as a "catch" and a "latch,"[17] with one deflecting and the other remaining rigid; there is no particular difference between which part does what.

Genc *et al*. (1998) classified these features and went on to provide a methodology for how to select one type over another for particular design and/or application situations. The variety of types is extensive, as shown earlier in Figure 2.22 and as can be further seen in manuals for snap-fit attachment design (see bibliography at the end of this chapter).

Snap-fits are widely used for assembling plastic parts because intricately shaped features can be easily produced by various plastic molding processes. They have begun to find their way into metal structures as well. One European automobile manufacturer (Audi) has explored the possibility (with an aluminum-producing partner) of using snap-fit assembly of machined extruded tubes into machined cast fittings to assemble structural space-frames for aluminum-intensive vehicles for the future.

The advantages of "snap-fits" are (1) low insertion force (relative to the retention or locking force that can be obtained); (2) high retention force (relative to the low insertion force needed to cause assembly); (3) simple insertion motions (e.g., "push," "slide," "tilt," and "twist"); (4) easy automation of assembly as a result of the easy motions and low forces required; (5) tactile and audible feedback to ensure full insertion, engagement, and locking (i.e., built-in quality assurance); (6) convenience associated with there being no small pieces to handle during assembly; (7) safety associated with the lack of small pieces, which children could ingest if they accidentally disassembled toys, for example; and (8) good resistance to accidental assembly with proper design precautions. This final point deserves repeating: Unintended accidental disassembly can be prevented by careful design using a combination of sequential motions to cause assembly (which virtually could not occur accidentally in the reverse sequence and directions), or locking pieces, (such as "keys") to block reverse deflection of the elastic feature. An example of the use of different assembly/disassembly motions that must be performed in the right sequence is seen in the childproof pill container, which requires a push and twist to install the cap and an opposite twist and pull to remove it.

Two cautionary notes are (1) accidental disassembly can occur, especially if parts deflect under loads (as upon impact from dropping); and (2) keeping snap-fits under sustained elastic stress by not allowing partial (if not full) recovery upon full engage-

[17] The terms "catch" and "latch" are best exemplified by the features that allow a door to click into place in a jamb. A feature that can somehow deflect is caused to deflect by a mating feature on the mating part. The protruding feature is called the "latch" and the recessed feature is called the "catch." Either the catch or the latch can be elastic (or rigid), so long as one behaves elastically and the other rigidly. Also, the catch or latch can be on the door as long as the mating feature is on the jamb.

ment can lead to feature failure and loss of locking due to stress relaxation in susceptible materials like plastics and wood.

It is also possible to use elastic recovery stresses to lock parts together as the result of thermal expansion or contraction, or interference fits. In "thermal shrink-fits," one part is heated or cooled relative to another, the two parts are mated, and the temperature is allowed to equilibrate. Once the temperatures of the two parts become the same, the heated part contracts (or the cooled part expands) to develop what are usually limited to elastic stresses that hold the two parts together with at least friction. There could possibly be some more macroscopic interlock. An impressive example of this was used to install removable liners into the barrels of the 16-inch-diameter guns of the great battleships of WWII. By shrink-fitting these liners into place, the plan was that they could be removed and replaced when they experienced unacceptable wear. Regrettably, the details of how they would be removed were never documented, so no liner has yet been removed!

It is also possible to force a "big pin into a small hole," creating what is known generically as an "interference fit" and specifically as a "press-fit." Depending on how much larger the internal part is than the hole in the external part, the resulting stress might be only elastic or it might be plastic. In either case, the one part is locked into the other. A common example of "press-fits" is bearings pressed into housings.

3.5.5 Plastic Integral Mechanical Interlocks: Part Alteration to Accomplish Joining

It is sometimes necessary (beyond possible and desired) to lock two or more parts together by altering the features of those parts somehow to prevent movement after assembly. The most readily apparent method of altering the parts is by employing plastic deformation. In fact, several methods of joining parts rely on plastically deforming interlocking mechanical features, including (1) "formed tabs" or "tab fasteners"; (2) formed or co-formed structures; (3) crimping; (4) hemming (which involves forging or pressing—known as "ironing"—one part around another, as on automobile exterior-to-interior seams of body panels); (5) staking or "setting"; and (6) interference press-fitting. Naturally, for such methods to work, the materials comprising the parts being joined must usually be inherently plastic (although there are exceptions), and the parts must have geometry that is amenable to being plastically deformed (both without degradation of properties). Elastic recovery often contributes to the gripping action of plastically formed-in geometric interlocks and interferences. Not surprisingly, metals and plastics (especially thermoplastics), particularly in sheet forms, are particularly suited to this form of integral attachment or joining.

The forming of interlocking tabs ("tab fasteners") in sheet-metal parts is a simple and inexpensive way to achieve joining between sheet-metal parts. The formed-in tab is useful for holding parts in place only as long as the applied forces and resulting stresses that must be resisted are low and, ideally, not in the direction opposite from that used to form the tab. Closely related to formed tabs are "formed" or "co-formed" features. A few examples of these important methods for sheet metals (and also for thermoplastics) are shown in Figure 3.43.

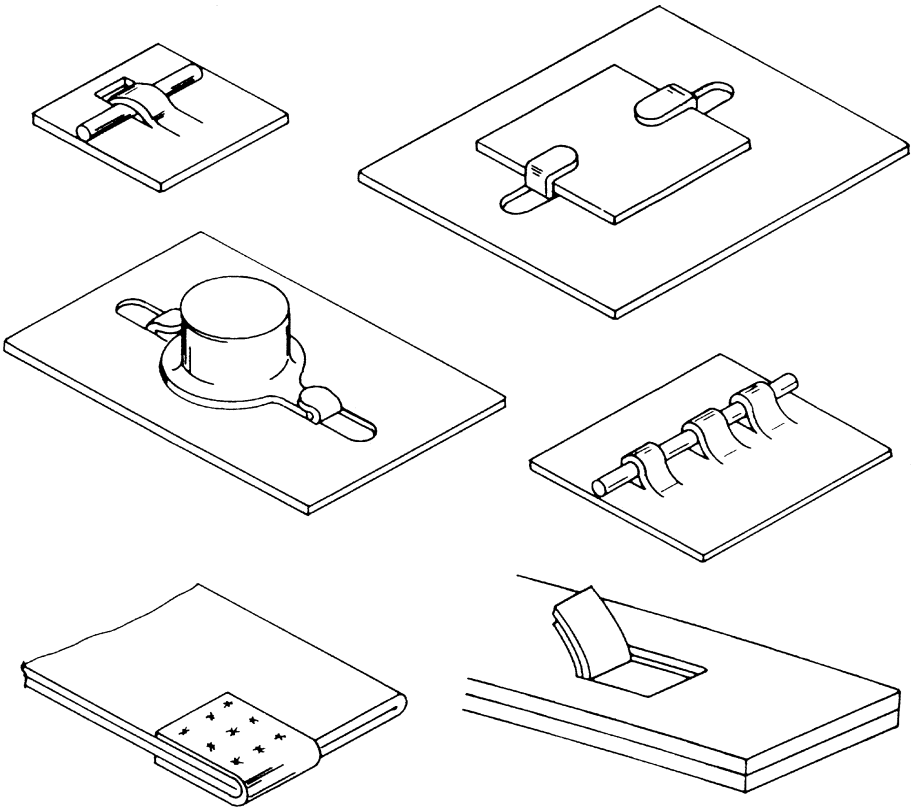

Figure 3.43 Schematic illustration of some important formed-in plastic interlock features widely used in the assembly of sheet-metal parts. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.32, page 101, with permission of Elsevier Science, Burlington, MA.)

While with tab fasteners and formed features the detail parts are sometimes deformed during their fabrication before assembly, a new technique called "stitch folding" joins up to three plies of sheet metal to a total thickness of 2 mm (0.080 in.). The resulting folds resemble the dog-ears schoolchildren form into stacks of paper by folding and tearing at one corner to accomplish simple joining. Shear strengths of stitch-folded joints in sheet metal can approach 80–90% of those of comparable riveted joints, and each stitch fold can be made in less than a second with a special tool marketed under the trade name Tagger.

Crimping and *hemming* are similar processes, both of which join metal parts by plastically deforming the two pieces while they are in contact to cause interlocking. In *crimping,* one piece is crushed, squeezed, or otherwise deformed around another to prevent relative movement. Occasionally a soft, malleable metal is sandwiched between the folded or crimped features to facilitate clamping by better complying with the part around which the crimp is being made. As an example, metal wires are commonly

plastically deformed by crimping into terminal or connector bodies in electrical assemblies. In *hemming,* a linear joint is formed by plastically folding one piece of sheet metal over or around another to create an immovable seam. Sheet-metal parts such as the outer and inner skin panels of automobiles (e.g., doors, hoods, and trunk lids) are often plastically deformed by hemming unless they are spot welded.

Staking and *setting* are methods of preventing axial sliding or rotation by using a punch to create a deformed impression at the mating surfaces or junctions of two parts. This results in an interlocking bump and depression or recess that prevents relative movement.

Figure 3.44 shows the methods of crimping, hemming, and staking or setting, while Figure 3.45 shows a typical hemmed joint in a modern automobile body panel.

Another useful and increasingly popular method of using plastic deformation to join metal or plastic parts together is marketed under the trade names of Tog-L-Loc and Lance-N-Loc (BTM Corporation, Marysville, MI). In these methods, deep recesses are pressed into a two-piece stackup of sheets. The top piece is literally forced down into the mating recess of the bottom sheet. This creates an interlock with the combination of elastic recovery and, sometimes, use of re-entrant angles or features. Examples of a Tog-L-Loc and a Lance-N-Loc are shown schematically in Figure 3.46.

3.6 OTHER MECHANICAL JOINING METHODS

3.6.1 General Description of Other Methods for Joining Parts Mechanically

There are some other ways to join parts using mechanical forces. Some of these are really just special forms of fasteners that are supplemental mechanical parts or devices that create interference and cause interlocking of parts being joined (e.g., stapling and stitching or sewing). Some are truly methods of mechanical fastening in the pure sense of the definition given above, but the "supplemental devices" (e.g., laces, lashings, knots, and wraps) look far less like traditional fasteners. Still others really employ actual parts to cause an assembly of those parts to operate together in an assembly. So while it might be difficult to see or consider methods using couplings and clutches to be mechanical joining, they are valid mechanical joining approaches. Finally, there is the possibility of using magnetism to hold parts together, such as those decorative magnets that hold children's report cards on the refrigerator door.

3.6.2 Stapling and Stitching or Sewing

It is often possible to join two or more materials together by tying them with a fine wire, fiber, or filament. Stapling and stitching or sewing are common examples.

In *stapling,* fine (usually metal) wires are formed into U-shaped fasteners and driven through thin sheets of the materials to be joined. The staple makes its own holes as it goes, and the staple often locks into the pieces by having its protruding ends

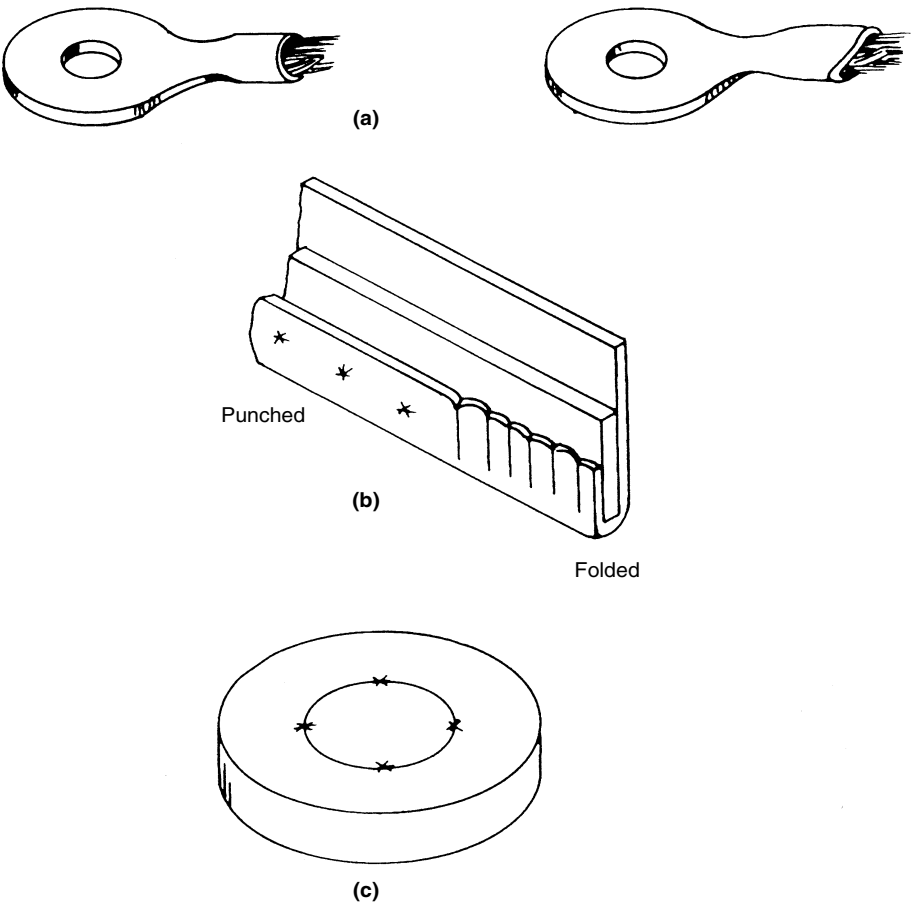

Figure 3.44 Schematic illustration showing the methods of crimping (a), hemming (b), and staking or setting (c). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.33, page 102, with permission of Elsevier Science, Burlington, MA.)

deform orthogonally inward or outward. This locks or cinches the staple in place and the pieces together, preventing the staple from being withdrawn accidentally. In other cases, the staple is held in place just by the friction of the elastically deformed hole it produced. In *stitching* or *sewing*, a continuous fiber or filament (e.g., thread or wire) is passed through holes formed in mating pieces of material by a needle, locking the pieces together with the continuous fiber. The fiber or stitch behaves like a fastener, preventing relative movement between parts either under shear using bearing forces between the stitch and the materials being sewn or under tension using tensile forces in the stitch, or both.

Stapling and stitching have long been used with cloth, leather, and even skin or other living tissue. More recently, methods were developed for stapling or stitching

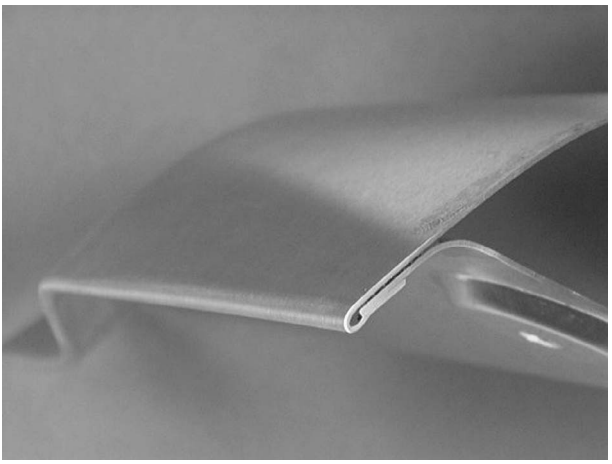

Figure 3.45 Close-up photograph of a typical so-called 3-D rope hem in sheet-gauge steel external body panels (on the left in this photo) and internal stiffening panels of a modern automobile. (Courtesy of the Ford Motor Company, Dearborn, MI, with permission.)

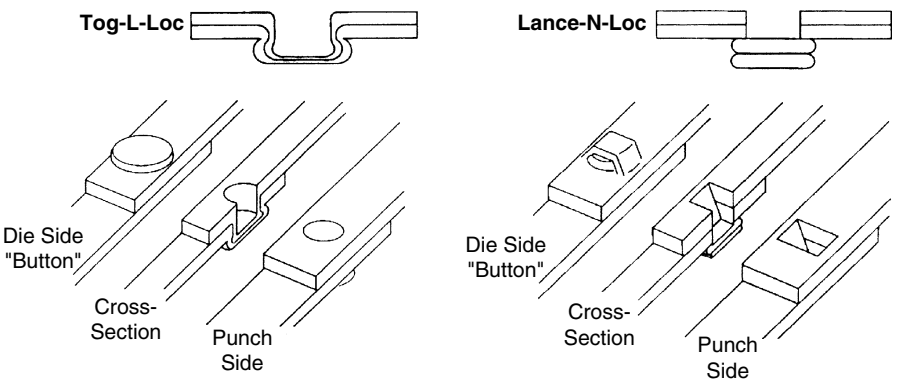

Figure 3.46 Schematic illustration of Tog-L- Lok (left) and (b) Lance-N- Lok (right) formed-in plastic locking features. (Reprinted from *User's Guide for BTM's Tog-L-Loc and Lance-N-Loc Sheet Metal Joining Systems*, BTM Corporation, Marysville, MI, 1991, with permission.)

sheet metals (e.g., soft, thin tin, aluminum, copper, brass, and even steel). Today stapling and stitching are being used with laminated, polymer-matrix as well as carbonaceous-matrix composites. In these materials, the staples or stitches literally tie layers together. By selecting the proper staple or filament material (for example, the same as the reinforcing fiber in the composite), the through-the-thickness strength of a laminate can be increased significantly over the strength attained with the resin matrix or a similar bonding agent (e.g., adhesive). Examples of these methods are shown in Figure 3.47.

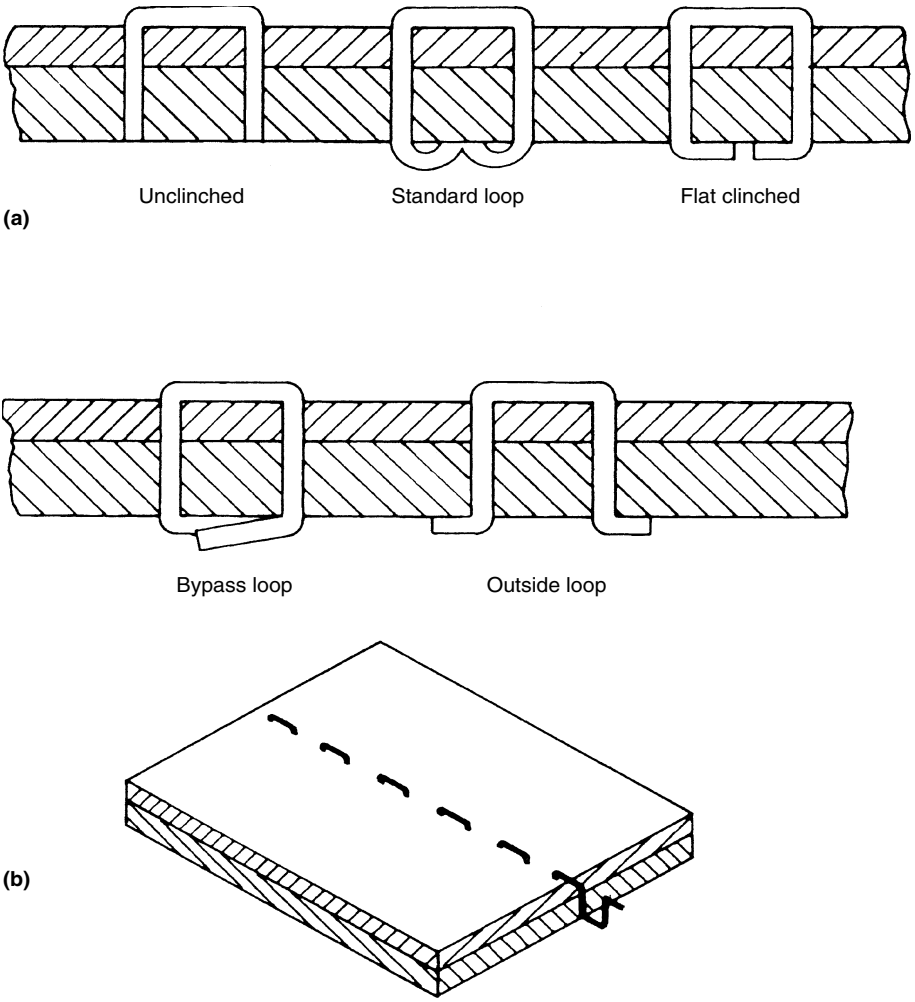

Figure 3.47 Schematic illustration of various types of stapling (a) and of typical stitching (b) as joining methods in soft materials. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, 1993, Fig. 3.34, page 103, with permission of Elsevier Science, Burlington, MA.)

3.6.3 Laces, Lashings, Knots, and Wraps

Related to the methods of mechanical fastening described in the previous subsection are lacing, lashing, tying (or roping), knotting, splicing, and wrapping. Although these methods are important, and have been and continue to be used in structural applications, they are not generally used with advanced materials or for many modern engineering applications. This being said, a very brief description of each will be given, referring the

interested reader to special references on these methods, such as Laughner and Hargen (1956) and Parmley (1989).

Laces are fibrous straps or cords that are used to tighten an outer part onto an inner part or abutting parts by passing the laces through eyelets in the one part, pulling the opposite ends of the strap to pull opposing pieces containing the eyelets together, and repeating the process until all eyelets are pulled as tightly together as possible or as needed. The most familiar example is the use of laces to tighten shoes onto one's feet.

Lashings are similar to laces, but may or may not use eyelets. Also, lashing tends to be more substantial, with ropes replacing laces. A well known example is the way a sail is lashed to a boom on a sailboat.

Knots are interlocks created in fine fibrous threads, laces, or ropes produced by looping the rope (for example) around and through itself to create a self-interlocking feature. Knots can be used to join one piece of rope (for example) to another, or to a part around or through which the rope is passed. The knot remains tight (and sometimes even further tightens) against forces that attempt to pull it apart. It is effective because of macroscopic interference and interlocking of one portion of the rope against another portion, as well as becuase of friction between portions of the rope against itself or against the parts it ties together. Related to knots are splices, although splices are actually methods of entwining strands in a rope or cable to join one to another without any obvious protruding feature as always found with knots. Figure 3.48 shows some important knots as well as an important splice.

Wraps are done to keep a multi-stranded rope or cable from unraveling, or to loop a multi-stranded rope or cable back onto itself. Wraps are made by winding a fine wire or tape or other strong, fibrous material around the circumference of a rope or cable to gird it.

3.6.4 Couplings and Clutches

Couplings are actual mechanical parts designed explicitly to join or couple two parts, one to the other. Parts that are coupled usually operate by rotating, so couplings tend to be placed between them at the ends of the rotating members, such as shafts. Another common use of couplings is to connect two pipes or tubes or hoses together, end to end. Couplings are often custom-designed for a particular job, but standardized couplings also exist for standardized shafts, tubes, pipes, hoses, etc. Clutches are special devices used to connect or link or couple two rotating parts together, either temporarily or intermittently, or to allow one part to decouple from another if something happens that causes one or the other rotating part to forcibly stop or need to stop. The interested reader is again referred to any of a number of good machine-design handbooks (see the cited references in Chapter 2 or Parmley (1989)).

3.6.5 Magnetic Connections and Fasteners

Every refrigerator in every home with children has drawn or painted pictures, good report cards, and reminder notes held in place by magnets (usually with some

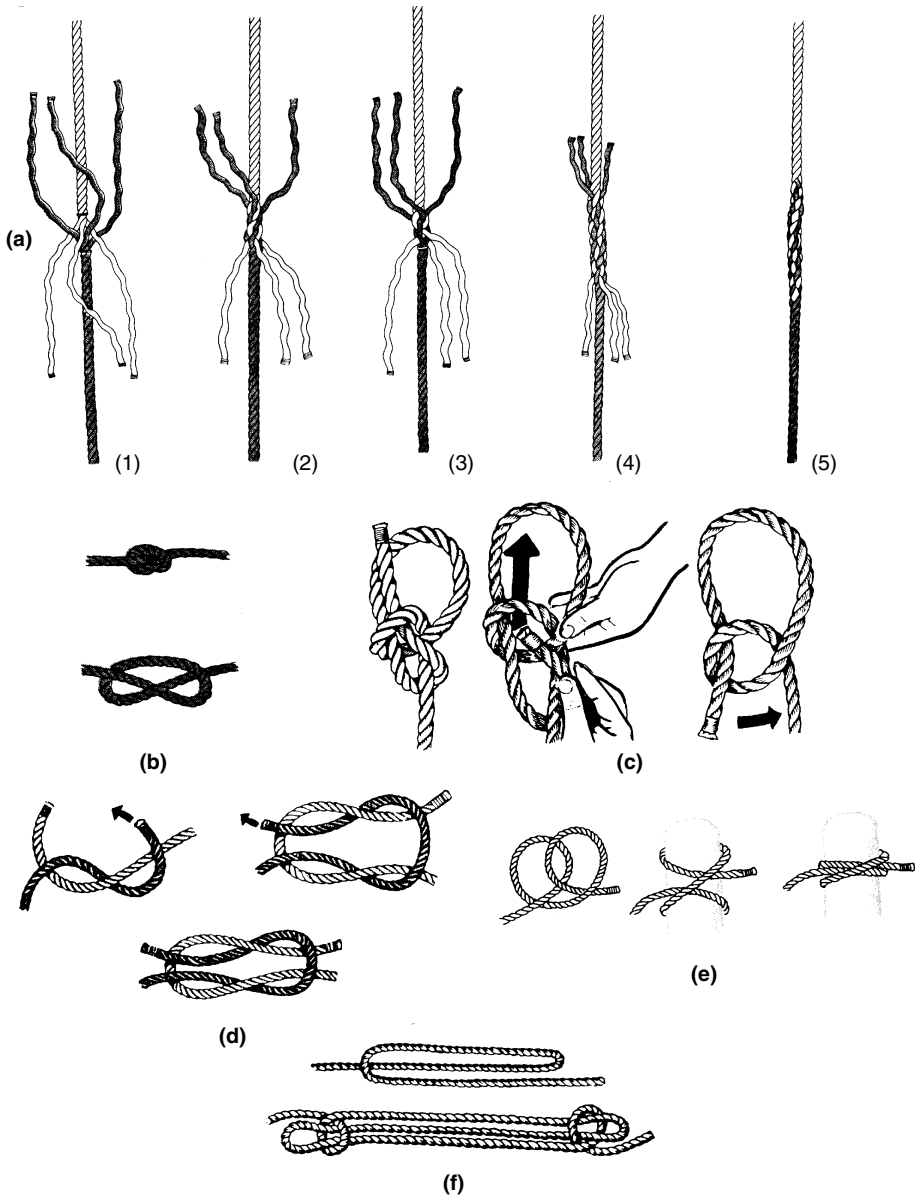

Figure 3.48 Schematic illustration of a typical splice and some important knots used to join ropes and cables, including (a) short splice, (b) overhand knot, (c) bowline knot, (d) square knot, (e) clove hitch, and (f) sheepshank knot. (Reprinted from various figures in Chapter 19 of *Standard Handbook of Fastening & Joining*, 2nd ed., R.O. Parmley, McGraw-Hill Publishing, New York, NY, 1989, with permission.)

interesting and decorative motif). Besides these, however, magnetic connections and fastening devices (as opposed to pure fasteners) have been—and continue to be—used to fixture parts, lift parts, clamp parts, etc. In such devices, a clamping force is created by the force of magnetic attraction between the magnetic device and the part to which it is connected. Obviously, both the magnetic connections or fastening devices and the part to which they are attached must be ferromagnetic. Hence, materials involved are Fe-based, Ni-based, Co-based, or special rare earth magnetic metals or alloys, or certain ferromagnetic ceramics (e.g., ferrites).

SUMMARY

Mechanical joining is accomplished using either of two fundamental approaches: (1) supplemental devices or parts in *mechanical fastening;* or (2) naturally occurring, designed-in and pre-fabricated, or processed-in features in *integral mechanical attachment*. Both approaches cause joining by first creating interference or interlocking, or vice versa. Mechanical fasteners can be classified as *threaded fasteners* or *unthreaded fasteners,* with the former using a helical ramp or "thread" on or in the fastener to create a clamping action upon tightening by rotation, and the latter relying strictly on the device or fastener itself to create a wedging force or simply resist shear loads through bearing of the fastener against the joint element(s). Threaded fasteners include bolts, screws (typified by machine screws), nuts and lock-nuts, and tapping or self-tapping screws, all of which employ standardized thread designs in either Unified Inch or Metric Series. Unthreaded fasteners include the more diverse types of upsetting rivets, blind (often two-piece) rivets, self-setting or self-upsetting rivets, pins (including pegs and nails), eyelets and grommets, retaining rings and clips, keys and keyways, and washers and lock-washers.

Integral mechanical attachments can be logically classified into rigid, elastic, and plastic types based on how they are formed or carry loads, or both. Each particular type tends to be suited for use in materials or joint elements, which themselves behave rigidly, elastically, or plastically in the way in which they respond to joint loading. Rigid types, such as dovetails, tongues-and-grooves, and mortise-and-tenons, are popular in wood, ceramics (including stone, brick, cement, concrete, and engineered ceramics), glass, and hard and/or strong metals (like cast iron or tool steels), and rigid polymers (especially thermosets). Elastic types (typified by "snap-fits") are popular in polymers and metals. Plastic types (like crimps, hems, and stakes) are popular in soft, malleable metals and polymers, especially thermoplastics. Other methods for mechanical joining tend to use fastening elements or parts that are less recognizable as fasteners but are really still fasteners in the purest sense. These include staples, stitches (in sewing), laces, lashings, knots and splices, wraps, couplings and clutches, and magnetic connections and fasteners.

QUESTIONS AND PROBLEMS

1. The basis for all mechanical joining is physical interference and/or interlocking rather than chemical reaction or bond formation. Such interference or interlocking can occur at the macroscopic level (in the actual components or components' design features) or at the microscopic level between material features (i.e., surface asperities). Describe several ways that macroscopic interlocking is used to accomplish mechanical joining. Specifically consider the role of such interlocking with fasteners, with integral design features, and with part alteration by plastic deformation.
2. Related to the statement made in Problem #1, explain what role microscopic interlocking plays, including in mechanical fastening with threaded fasteners, with unthreaded fasteners, and with integral rigid and elastic design features.
3. Other than the obvious fact that one is threaded and the other is not, what differentiates the way in which threaded fasteners accomplish joining versus the way unthreaded fasteners do?
4. Explain how the threads on a threaded fastener work to enable joining with these devices.
5. Completely describe the bolt designated by each of the following call-outs:
   - 5/16-18 UNC, Class 2.
   - 5/16-24 UNF, Class 3.
   - MJC 70×1.5.
   - MJF 10×0.75.
6. Explain what is meant by the "grade marking" on the head of a steel bolt, in general, and by the specific markings on the two bolt heads shown below: [no bolt heads shown]
7. What is the principal difference between screws and bolts? What might be some secondary differences? What is the principal difference between screws and tapping screws?
8. Describe at least four techniques that are used to prevent the unwanted loosening of nuts in service. What are some limitations of each technique?
9. What is meant by the term "locknut"? Describe three major approaches used in these fasteners to prevent unwanted loosening.
10. What is meant by "integral fasteners"? Why are they used? Where might they be particularly useful? Give some examples of integral fasteners, preferably beyond those described in this chapter.
11. What are the similarities and the differences among "integral fasteners," "self-clinching fasteners," and "cast-in" or "molded-in" fasteners?
12. Differentiate between the ways in which rivets and bolts accomplish joining. For which type(s) of joint loading is each preferred, and why? (Hint: see Chapter 2)
13. Explain what is meant by "blind rivets." Give two examples of generic application situations where such fasteners would be useful or required. What sacrifices, if any, must be made in using blind rivets as opposed to conventional upsetting rivets or bolts?

14. Describe a couple of designs for "blind rivets."
15. Differentiate among the following: (1) "self-upsetting rivets," (2) "self-setting rivets," and (3) "self-piercing rivets."
16. Describe "pins" as mechanical fasteners. How do pins differ from rivets and bolts in their primary function(s)? Give some examples of situations in which pins are used.
17. Describe how "nails" hold two pieces of wood together (a) in shear and (b) in tension. What, if anything, can be done to improve the load-carrying capability of nails in tension? Give several examples of what can be done.
18. Describe where and how "retaining rings and clips" are used in mechanical assembly.
19. Give several reasons why "eyelets" are useful fasteners in wearing apparel and sailboat sails, for "tie-down," for example. Give several examples of where "grommets" are used.
20. What are the major functions of "washers" in mechanical fastening?
21. Describe what is meant by "rigid interlocks," and give some examples with which you are familiar in wood assembly, cement or concrete construction, glassware, and high-strength metals.
22. Describe what is meant by "snap-fit" integral attachment features. Why and where are these devices particularly useful? Describe two generic designs for snap-fit features.
23. What is it about "snap-fits" that allows them to have higher retention forces than insertion forces? Explain how the "snap" characteristic of such features is useful for quality assurance.
24. Give some examples of "integral design features" used for accomplishing interlocking in which engagement is caused by a simple "push," a simple "slide," a simple "tilt" (like about a hinge), and by a simple "twist" to "rotation." Explain why the "child-proof" cap on prescription medications is especially resistant to accidental opening.
25. Describe several basic ways in which parts can be joined by altering their basic features during or just after assembly.

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Chapter 4

Adhesive Bonding and Cementing

4.1 INTRODUCTION

Materials and the structures they comprise can be joined mechanically without any formation of atomic- or molecular-level bonds, by using only geometric interference and interlocking of naturally occurring, designed-in, or processed-in macroscopic as well as microscopic features (see Chapters 2 and 3). Joining can also be accomplished by actually forming interatomic or intermolecular bonds through a chemical process known as adhesive bonding. Another method (to be described in Chapter 6) is welding, which relies not so much on chemical interaction and reaction as on pure electromagnetic interaction among the atoms making up the materials to be joined.

The process of adhesive bonding is actually quite old, having its origins in the joining of many materials and objects using naturally occurring agents such as tree saps and pitch, tar, and various other plant and animal extracts or excretions (see Chapter 5, Subsection 5.3.2). This process began to gain serious technical credibility and appreciation only within the last half of the 20^{th} century. For much of the time before that (and, regrettably, even now!), adhesive bonding was a rather technically unsophisticated but successful method for joining a wide variety of materials, including paper, fabrics, wood, leather, various plastics and rubbers, glass, and ceramics, especially stone, bricks, and cement and concrete products. Except for its use with wood and various porous ceramic products (e.g., stone, brick, cement, and concrete), impressive structural applications have been limited. In its commonly known forms, adhesive bonding is referred to as "gluing," "pasting," or (especially for ceramics and glasses) "cementing." More recently, due mostly to the development and proliferation of synthetic polymers or plastics, adhesive bonding has emerged as a unique and increasingly technically sophisticated process. It has applicability to a wide variety of materials of more obvious engineering interest, including engineering thermosetting and thermoplastic polymers, electronic and structural ceramics, semiconductors, glasses, metals and engineering alloys, and various composites. Furthermore, adhesive bonding is now often used for primary structural, load-bearing applications, as shown in Figures 4.1 and 4.2, as well as for specialized nonstructural applications, such as sealing, insulation, and vibration damping.

Figure 4.1 Adhesive bonding is used in pleasure-boat manufacture. Here, a molded fiberglass deck and hull are being brought together for adhesive bonding. Adhesive can be seen already in place along the center portion of the aft transom, above a masked area. (Courtesy of Wellcraft Marine Corporation, Sarasota, FL, with permission.)

Figure 4.2 An old bridge on Mount Desert Island, ME, constructed from cut stones held together, or ''bedded,'' using cement or mortar. (Photograph by Robert W. Messler, Jr.)

As a joining process, adhesive bonding offers many advantages, some of which make it unique. It also has limitations that must be well recognized and carefully considered during the design process, as well as in service. This chapter looks at the process of adhesive bonding, its general description, its relative advantages and disadvantages, and the mechanisms proposed to explain or at least rationalize how joint strength is obtained. The modes and mechanisms of bond failure, the requirements for producing a good bond, and joint design and design analysis methodology and criteria will also be discussed. In Chapter 5 the actual agents used to accomplish adhesive bonding (i.e., "adhesives") are addressed.

4.2 ADHESIVE BONDING AS A JOINING PROCESS

4.2.1 General Description of Adhesive Bonding

Adhesive bonding is the process of joining materials with the aid of a substance, acting as a chemical agent, capable of holding those materials together by surface attachment forces. The materials being joined are called the *adherends*, while the bonding agent is called the *adhesive*. The forces that enable the surface attachment arise from one or more of several fundamental sources, most of which are chemical in origin, but some of which can be mechanical or even electrostatic. These forces give rise to what is known as "adhesion," which is the sticking together of different materials. The chemical sources lead to the actual formation of chemical bonds—principally, but not solely, secondary types. Thus, adhesive bonding is fundamentally a chemical bonding process.

There are really two major manifestations of adhesive bonding: (1) *structural adhesive bonding* and (2) *nonstructural adhesive bonding*. In structural adhesive bonding, the primary intent of the process and of the adhesive is to develop sufficient strength in the joint and adhesive that the adherend or substrate is stressed to near the point that either the adherend or the adhesive fails. Such failure would occur by plastic yielding or fracture in either a ductile or brittle fashion, depending on the type, condition, and strain behavior of the adhesive. This allows the designer to take full advantage of the adherend's strength and results in high joint efficiencies (see Subsection 1.7.2). To fulfill their intended function, structural adhesives must be capable of transmitting stresses without losing their own integrity, within the limits of the design.[1] Typical examples of the use of structural adhesive bonding are shown in Figure 4.3, where joining of glass-, aramid-,[2] and graphite-reinforced thermosetting and thermoplastic polymer-matrix composites, and various metal-to-metal and metal or polymeric honeycomb joints are used in modern aircraft assembly. These include so-called "primary" potentially flight-critical structures.

In nonstructural adhesive bonding, on the other hand, the adhesive agent is used for some primary purpose other than for its structural strength and integrity. Examples

[1] With proper selection and use, adhesive shear strengths of 50 MPa (more than 7,000 psi) can be obtained from so-called "organic" (actually, polymeric) types.

[2] *Aramids* are a particular group of polymers based on a long-chain synthetic polyamide in which at least 85% of the amide linkages are attached directly to two aromatic rings.

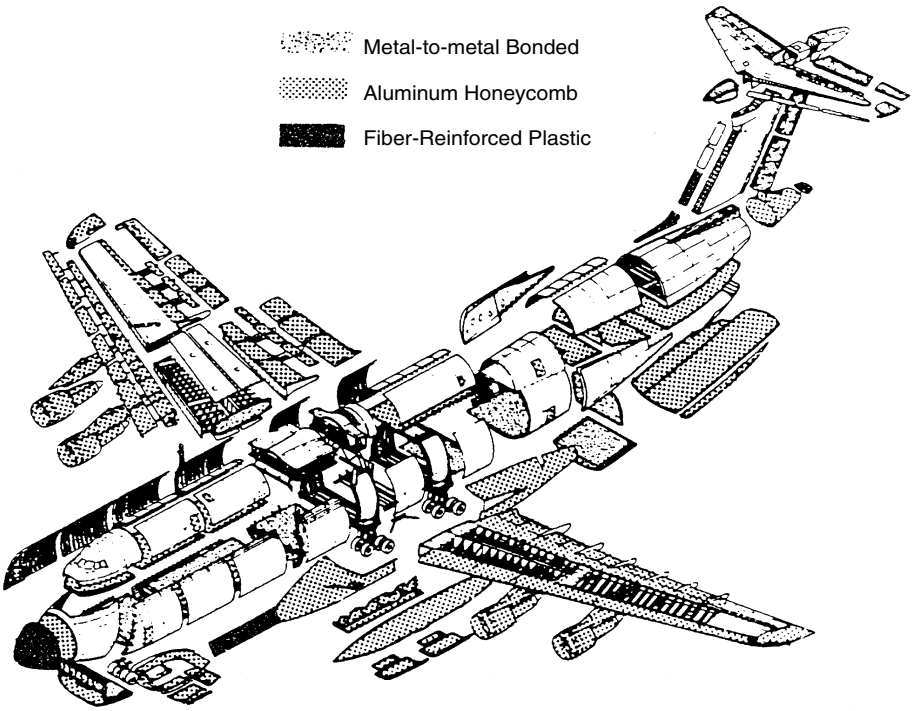

Figure 4.3 A schematic illustration showing the areas and types of adhesives used in structural and secondary bonding in modern aircraft. (Reprinted from "Adhesives for Aerospace", L.E. Meade, Fig. 6, page 345. In *Joining Technologies for the 1990s*, J.D. Buckley and B.A. Stein, Eds., Noyes Data Corporation, Park Ridge, NJ, 1986, with permission of William Andrew Publishing, Norwich, NY.)

are for sealing to preclude fluid loss or intrusion (i.e., leaks), electrical and/or (to a lesser extent) thermal insulation or vibration damping and sound deadening. Nonstructural adhesive bonding has been and continues to be widely used in the assembly of modern automobiles and has been a major contributor to better resistance to corrosion from unwanted moisture intrusion. It also improves "ride" through vibration damping and sound deadening. Regrettably, the failure of adhesives formulated for nonstructural applications under structural loads has caused concern about adhesive bonding in designs for structural applications. Such concern is unwarranted because the adhesive was misused. After all, "structural" is structural, and "nonstructural" is not!

The focus of this chapter will be structural adhesive bonding, although most of the principles discussed apply to nonstructural adhesive bonding as well.

4.2.2 Cementing and Mortaring as an Adhesive Joining Process

An extremely important (but surprisingly and disappointingly largely unrecognized) type of adhesive bonding involves the use of cements and mortars in the construction of

Figure 4.4 Laying brick using mortar or cement. (Courtesy of the National Precast Concrete Association, Indianapolis, IN, with permission.)

masonry structures. This may be because masonry lies at the intersection of architecture and engineering, often being the uneasy ''stepchild'' of both. Without question, more adhesive bonding involves the use of cements and mortars than not only all other forms of adhesive bonding, but all other forms of joining as well! This is virtually inevitable given that stone, bricks, cement, and concrete, as a group, represent nearly half of all the material used for all manufactured products and structures per year, irrespective of the measure (e.g., English or metric tons, cubic yards or meters, or dollars, Euros, or yen).

Masonry involves the construction of structures from one of more of the following materials or material forms: stone (both naturally occurring and shaped types); so-called ''clay units'' represented by bricks of all types; and so-called ''concrete masonry units'' represented by blocks and pre-fabricated concrete shapes of all types. These forms (especially the first two) have been used since ancient times, with structures being built up from these units either ''laid dry'' (relying strictly on mechanical interlocking, as described in Chapters 2 and 3, Section 2.8 and Subsection 3.5.3), or ''bedded'' in soil, clay, mortar, or cement. Obviously, being ''bedded'' with clay, mortar, and/or cement adds some degree of actual chemical bonding (i.e., adhesive bonding) to pure mechanical interlocking. Figure 4.4 shows bricks being ''bedded'' in cement, in what is known as ''bricklaying.'' The operation of cements and mortars will be covered in Chapter 5, Section 5.6, while the joint designs in stone and brick masonry and in cement and concrete construction will be addressed in Section 4.7 of this chapter.

Table 4.1 lists the various forms of adhesive bonding by both primary and secondary types.

Table 4.1 Various Forms of Adhesive Bonding

Natural Adhesives
- Animal-based adhesives (e.g., casein, collagen, gelatin, lac)
- Plant-based adhesives (e.g., pitch, natural rubbers, asphalt)
- Mineral-based adhesives (e.g., sodium silicate, water glass, mineral-based sol-gels, calcium carbonate)

Synthetic Adhesives
- Synthetic Organic Adhesives
  - Chemically-activated adhesives (e.g., anaerobics, cyanoacrylates, epoxies)
  - Heat or radiation-activated adhesives (e.g., one-component epoxies)
  - Evaporation or diffusion adhesives (e.g., phenolics)
  - Thermoplastic hot-melt adhesives
  - Pressure-sensitive (contact) adhesives
  - Delayed-tack adhesives
- Synthetic Inorganic Adhesives
  - Portland cements
  - High-alumina, calcium aluminate cements
  - Mortars (e.g., gypsum)
  - Refractory cements
  - Dental cements
  - Glassy frits

4.2.3 The Functions of Adhesives

The principal function of adhesives is, obviously, to join materials together, which thus joins structures. Adhesives do this by transmitting stresses from one element of a joint (or one adherend) to another in such a way that the stresses are distributed more uniformly than in most, if not all, mechanical methods and many welds. This is true for several reasons. First, unlike for almost all mechanical fasteners, no holes are introduced into the joint elements to allow joining. Without holes, a load that is uniformly applied to a joint element is carried uniformly by the entire joint element (at least for a uniform cross-section), as shown in Figure 4.5a. If a hole is present in the joint element to allow a fastener to be installed, for example, then the applied loads must be carried by the material remaining in the joint element, since no load can be carried by material that is not present in the hole. Thus, the presence of a hole leads to a concentration of stress (i.e., load per unit area of cross-section) in the joint element, as shown in Figure 4.5b.

Second, in virtually all cases where they are used properly, adhesives fill the entire joint and create bonding forces (whatever their origin) over the entire area of the joint, rather than at discrete points of attachment (as with fasteners and most integral attachment features).

Third, regardless of the specific mechanism by which an adhesive develops joint strength, the larger the area over which the adhesive is applied and acts to carry loads,

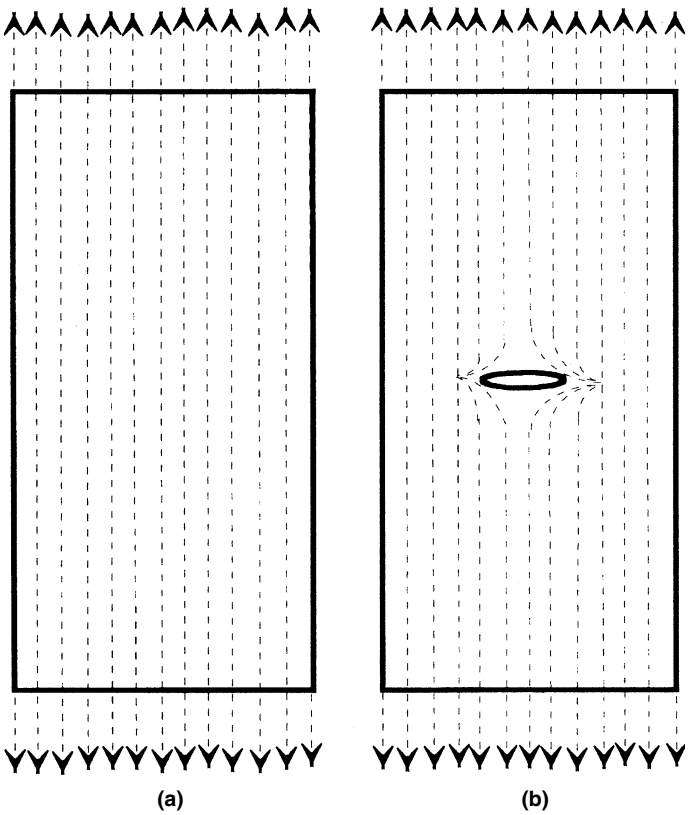

Figure 4.5 Schematic illustration of uniform stress distribution in a uniformly loaded structure (a) versus stress concentration around holes or defects in the same uniformly loaded structure (b). (Reprinted from *Adhesion and Adhesives*, A.V. Pocius, Fig. 1.1, page 2, Hanser Publishers, Munich, Germany, 1997, with permission.)

the lower the stress that develops. These three factors combine to enable adhesives to carry considerable loads, even if their inherent strength (i.e., load-carrying ability per unit area) is lower than for most fasteners, most integral attachments, and most welds. This, in turn, permits the use of lighter weight joint elements and, thus, lighter weight structural assemblies.

A fourth factor actually further contributes to most adhesives' developing lower and more uniform stress levels. Polymer-based adhesives (which constitute the largest proportion of all types of adhesives) exhibit viscoelastic strain behavior wherein an instantaneously applied or released load results in an essentially instantaneous strain response followed by a time-dependent strain response. While the degree and rate of the time-dependent strain response vary with the structure and stress–strain behavior of the particular polymer, the net result is a further "softening" of loads, both spatially and temporally.

This same viscoelastic nature of at least polymer-based adhesives[3] leads to some other important properties and, thus, functions for adhesives. Specially formulated flexible (e.g., "elastomeric" types or "blends") can readily accommodate large (i.e., generally considered to mean >15%) differences in thermal expansion coefficients between different adherends. In this way, flexible adhesives prevent damage that might otherwise occur if a stiff or rigid fastening system (e.g., bolting) or joining method (e.g., welding) were used. This is often an important consideration in terms of function. Flexible adhesives are also useful for providing mechanical damping to a bonded structure or assembly through their high internal friction.

Sealing is another important function of adhesives, particularly for nonstructural adhesives. The continuous nature of the bond typically provided by adhesives seals liquids or gases in or out, providing leak tightness and preventing intrusion of fluids that could lead to corrosion, even if not leaks. Adhesives used for sealing (i.e., "adhesive sealants") are often used in place of gaskets made of either solid or porous/cellular materials (e.g., cork). Sealing can also be accomplished by "potting" or "encapsulating compounds," which are really not true adhesives. They are strictly sealing agents.

Since adhesives are applied as a thin continuous film or layer over a typically large area, they can also be used to improve resistance to fatigue and to join thin or otherwise fragile parts (e.g., fabrics). In both situations, loading is distributed uniformly, thereby reducing the level of stress and preventing most severe stress concentrations. The ability of most organic adhesives to withstand static and dynamic (e.g., cyclic) strains and shock loads without cracking usually causes adherends to fail before the adhesives do, at least for properly selected adhesives and optimally bonded structures.

For most inorganic adhesives (of which cements and mortars are, by far, the most common, prodigious, and technologically and economically important), the distinct absence of viscoelastic behavior in favor of brittle elastic behavior tends to lead to preferential failure along the adhesive joint within the adhesive itself. Nevertheless, such adhesives are still capable of providing nonstructural benefits beyond structural strength, including thermal or (less commonly) electrical insulation and sealing against liquid leaks or intrusion.

4.2.4 Advantages and Disadvantages of Adhesive Bonding

As a process, adhesive bonding offers many advantages compared to other joining processes, some of which are unique. Besides mechanical joining (i.e., fastening or integral attachment), adhesive bonding is the only joining process that does not change the microstructure of the materials being joined. It usually causes little or no chemical alteration, either. This can be important in and of itself because by not changing the materials it bonds, adhesive bonding never degrades the properties of the materials it joins. This characteristic also makes adhesive bonding rather uniquely suitable for

[3] As will become apparent later in this chapter, adhesives can be broadly classified as "organic" or "inorganic." For the most part, organic adhesives are based on polymers (either thermoplastic or thermosetting types), which always exhibit some form of viscoelastic behavior. Inorganic adhesives, which include various ceramic-based cements and mortars as their most common form, tend to exhibit strictly brittle elastic behavior.

joining dissimilar (as well as similar) materials in virtually any combination. In fact, adhesive bonding is often the very best choice for joining dissimilar materials, such as metals to polymers, metals to ceramics, ceramics to polymers, and monolithic metals or ceramics or polymers to reinforced metals or ceramics or polymers, in any imaginable combination. Since there is no mixing of adherends in any but the rarest cases, there are seldom problems with chemical incompatibility. In fact, because adhesive bonding isolates one adherend from another through an intermediate adhesive, it prevents galvanic corrosion better than mechanical joining processes. All that is required is that the adhesive selected be compatible with each adherend.

Other advantages of adhesive bonding, some of which are also unique, relate to the character of the adhesive and the nature of the usually large area and usually continuous bond produced, including (1) larger load-bearing area for high load-carrying potential; (2) more uniform distribution of stress and greater reduction of stress concentrations; (3) rather unique suitability for joining thin or thick materials (e.g., thin-to-thin, thick-to-thick, or thin-to-thick) of (4) virtually any shape (which is not easy for many mechanical fastening or integral attachment methods); (5) minimization or elimination of electro-chemical or galvanic interaction (e.g., corrosion) between dissimilar materials; (6) easy sealing (compared to mechanical joining) against a variety of environments, leading to improved corrosion resistance and hermeticity (i.e., leak tightness); (7) insulation against heat transfer or electric conductance (except when the adhesive is specially formulated to provide thermal or electrical conductivity); (8) dramatically improved resistance to fatigue and cyclic loads compared to all other joining processes; (9) unique damping of mechanical vibrations and absorption of shock loads; (10) easily achieved smooth joint contours for aerodynamic smoothness and/or aesthetics; (11) no reduction in the strength or other properties of adherends because of heat (versus fusion welding and brazing), as any required heat for curing the adhesive is usually too low to adversely affect the adherends (e.g., metals and ceramics); (12) provision of attractive strength-to-weight ratios, in that most adhesives are low-density materials, and they are applied in thin layers; and (13) the labor intensity for adhesive bonding is often low compared to riveting, bolting, and welding. These advantages are summarized in Table 4.2.

Although adhesive bonding can produce structures or structural assemblies that are more reliable than those produced by other joining methods, such structures or structural assemblies must be thoughtfully and carefully designed and used under conditions that do not exceed the known and planned-for operational limitations of the adhesive. Such limitations can be especially great for organic-type adhesives.

Limitations on loading and use include the types and directions of externally-applied and internally generated loads and the magnitudes of developed stresses, whether static or dynamic or both. Environmental factors are also relevant, such as temperature, humidity, the presence of solvents that can degrade the adhesive or its properties, and radiation from any of several sources. Specific limitations or disadvantages of adhesive bonding include (1) the requirement that the surfaces of adherends be properly and carefully prepared to obtain durable joints; (2) the imposition of rigid process control, with an emphasis on cleanliness, for maximum bond strength; (3) the

Table 4.2 Advantages and Disadvantages of Adhesive Bonding

Advantages	*Disadvantages*
• High load-carrying capacity possible due to large (surface) area bonding	• Sensitivity to peel or cleavage versus pure tension or shear
• Minimal stress concentration due to load-spreading over bond area	• Extremely complicated stress analysis required for critical applications
• Suitability to very thin as well as thick adherends	• Requires careful joint (adherend) surface preparation
• Causes little or no change to the chemistry or structure of adherends	• Requires rigid process control
• Suitability for joining similar or dissimilar materials	• Sometimes very limited working times
• Seals against many environments	• Curing times can be long
• Insulates against electricity or heat	• Direct inspection is not possible; NDE methods are needed
• Minimizes or prevents galvanic corrosion between dissimilar materials	• Repair of defective joints is virtually impossible
• Damps vibrations and shock loads	• Upper service temperature is very limited, especially for organic types
• Resists fatigue and imparts damage tolerance (with compliant adhesives)	• Life of joints is sensitive to the environment
• Attractive strength-to-weight ratio	• Sensitivity to attack by some solvents
• Provides smooth contours	• Many adhesives (especially natural types) are subject to attack by bacteria, molds, rodents, vermin, etc.
• Can be faster and cheaper than mechanical fastening or welding	

need for fixtures, tools, presses, ovens, and autoclaves that are not usually required for other joining processes (with the partial exception of some specific welding and brazing and soldering processes); (4) limited "working times" as well as "shelf lives" for adhesives, which complicate manufacturing logistics; (5) long "curing" or "setting" times may be needed, particularly where high curing temperatures cannot be used; (6) bonds do not permit direct visual examination of the bond area (unless the adherends happen to be transparent!), making inspection difficult; (7) repair of defective or deficient joints (regardless of cause) is virtually impossible due to inaccessibility; (8) upper service temperatures are limited to 180°C (350°F) in most cases for organic adhesives and 370°C (700°F) for specially formulated organic adhesives and many inorganic adhesives; (9) the useful life of the adhesive-bonded joint depends critically on the environment to which it is exposed, and environmental factors are much more diverse and restrictive than for other joining methods; (10) exposure to solvents used in cleaning joints, thinning adhesives, or solvent cementing may pose potential serious health hazards to workers; and (11) natural (e.g., animal- or vegetable-derived) adhesives are subject to attack by bacteria, mold, mildew, fungus, rodents, and vermin, which do not affect fasteners, integral attachments, welds, brazes, or solder joints. These disadvantages are also listed in Table 4.2.

4.3 MECHANISMS OF ADHESION

4.3.1 General Description of Mechanisms

Although much is known about particular aspects of adhesion, different and even widely divergent views and opinions exist with respect to other aspects. One thing is absolutely clear, however—there is no single mechanism or (perhaps even more frustrating) any unifying theory that satisfactorily explains all of what takes place in an adhesive-bonded joint. Without a unifying theory that relates the basic "physico-chemical" properties of adhesive and adherend materials to the actual mechanical (sometimes referred to as "physical") strength of an adhesive bond, it is sometimes said that there are really only "rationalizations" of adhesion phenomena, supported by experimental evidence. However, if the goal is to predict the strength of adhesive bonds from first principles (e.g., chemistry and chemical properties, physics, and materials science) of the adhesive and the adherends, as acted upon by the joint's geometry and operating environment, such rationalizations are good enough.

Before considering some of these rationalizations for the strength of adhesive-bonded joints in real materials or adherends, it is important and useful to consider some basic underlying mechanisms for forming joints between materials using a chemically-based approach (e.g., adhesive bonding). There are actually two key underlying principles or mechanisms, the first relating to the forces between adhesives and adherends that lead to their joining at all, and the second relating to the energy states of those two different material bodies.[4]

4.3.2 Force and Energy Bases for Adhesive Bonding

The forces that lead to all bonding in and between materials are those that arise as the atoms comprising those materials seek to attain stable electron configurations. For all but the inert, noble, or rare gases in Group VIII of the periodic table, atoms need to exchange (that is, give up, take on, or share) electrons so that the outermost occupied or valence electron shell of each atom is full. If actual exchange occurs, positive and negative ions are formed by giving up and taking on electrons, respectively, to just fill a shell. Oppositely charged ions then attract one another by purely electrostatic or Coulombic forces, forming a stable molecule or crystalline aggregate when the attractive electrostatic force is exactly balanced by the opposing repulsive force of the negatively charged outer electron shells as each ion begins to sense another's presence. At the point at which these two forces balance (that is, the equilibrium interatomic separation), the potential energy of the collection of ions is minimized, and "ionic bonding" is said to have occurred. If intimate sharing (as opposed to exchange) of electrons occurs between limited numbers of atoms to let each have a full valence shell "on average," then covalent bonding is said to have occurred within the resulting molecule. If this same type of sharing of electrons becomes more extended

[4] In fact, the foundation of physics is that all phenomena that occur in nature can be described when all the forces between bodies and the starting and final energy states of those bodies are fully described.

and delocalized, the array of atoms becomes more extended to form a regularly arranged aggregate of atoms held together by so-called "metallic bonding."

Once atoms attain stable electron configurations by bonding to form individual molecules or more extensive (regular crystalline or random amorphous) aggregates, forces still act to cause these individual molecules to further bond into more extended aggregates or molecular arrays, or to cause the aggregates to join together into larger aggregates. The forces leading to this further bonding can be additional primary ionic or covalent bonding in ceramics or metallic bonding in metals. Or they can be weaker so-called "secondary" bond types, the most common of which is the "van der Waal's bond." These arise from the interaction and attraction between either permanent or induced dipoles, known as "dipole–dipole" or "dipole-induced dipole" interactions. These forces are far weaker than ionic, covalent, or metallic bonds. Hence, the strength of any joints formed as a result of secondary (as opposed to primary) bonding is lower.

While these forces that lead to bonding (whether primary or secondary) act between atoms, ions, or molecules (henceforth referred to simply as "atoms") within a material, they also act between the surfaces of materials. Thus, bonding or joining between real materials (on a microscopic or macroscopic versus atomic scale) arises from "surface forces." These surface forces lead to the existence of a "surface energy" in materials.

Because all materials are finite (that is, they have physical limits on their size or extent), they have an "interior" or "bulk" and a "surface." For atoms located in the interior or bulk of a material, each one is surrounded by other atoms, and each atom is in a balanced state from the standpoint of interatomic forces. For atoms, at the surface of a material, however, this is not true. These atoms are being acted upon by other atoms from within or laterally, but not from the outside. This results in so-called "dangling bonds" or "unrequited valences." To counteract this imbalance of forces at the surface of all real materials, the atoms tend to be further apart, giving rise to a force acting in the plane of the surface. This leads to a "surface tension" that, in turn, gives rise to a surface energy. To reduce its total surface energy, any material that is able to do so forms a sphere.[5] Often, the only way to reduce the surface energy is to create an interface with more material of the same type (i.e., having the same chemical composition, atomic structure, etc.) or of a compatible type.

The combination of surface forces and surface energy in real materials is what causes them to "adhere" to one another in adhesive bonds or (as will be seen in Chapter 6) welds.

4.3.3 Theories or Rationalizations for Adhesive Bonding

Four theories or, more appropriately, rationalizations explain the process of adhesive bonding by explaining the underlying phenomena leading to adhesion. These four are (1) the electrostatic theory of adhesion; (2) the diffusion theory of adhesion; (3) the mechanical theory of (or mechanical interlocking contribution to) adhesion; and (4) the adsorption theory of adhesion. Let us look at each of these briefly, leaving

[5] A sphere has the smallest surface-to-volume ratio of any three-dimensional shape.

more thorough treatment to dedicated references such as Pocius (1997) or Kinloch (1987).

Electrostatic Theory of Adhesion. This theory attributes adhesion between an adherend and an adhesive to the development of electrostatic forces of attraction between the two at their interface. These attractive forces are assumed to arise from the transfer of charge between the two due to their relative differences in *electronegativity,* which is a measure of the strength of attraction between a particular atom and an electron. If an adhesive is designed and selected properly, an exchange of electrons can be made to occur between it and a compatible adherend, in one direction or the other. The resulting creation of oppositely charged layers (i.e., "polarization") at the interface between the adhesive and the adherend accounts for the resistance encountered in trying to separate them. Much of the force of adhesion comes from dipole interactions. Not surprisingly, this theory has particular relevance to materials that are insulators or dielectrics, such as polymers, glasses, and most ceramics.

Evidence supporting this theory has been found in the emission of light and charged and neutral particles when adhesive bonds are opened in a vacuum, as well as in differences in so-called "fringes of equal chromatic order" (or FECO) measured in a surface force apparatus (or SFA).

Diffusion Theory of Adhesion. This theory holds that when two materials are at least partially soluble in one another, they can and do form a solution at their interface. The mechanism for atom exchanges to form the solution zone is diffusion. This can be slow, solid-state diffusion between a solid adhesive and an adherend (which is always solid!), or faster diffusion between the adhesive when it is in a liquid form (e.g., melted or thinned with a solvent) and an adherend. The likelihood of such diffusion, and the resulting likelihood of strong adhesion, is greater for chemically similar adhesives and adherends, as when both are polymers. In such a case, the long-chain molecules of the adhesive and/or adherend may be mobile enough to interdiffuse and entangle due to entropy. Entanglement is known to be extremely important in the joining of polymers. Two subtypes of adhesive bonding where diffusion undoubtedly plays a significant role are "solvent cementing" and "fusion bonding" of thermoplastics (see Chapter 13).

It is difficult to apply this theory to the adhesive bonding of metals or ceramics, where interdiffusion with most adhesives, regardless of their type (i.e., organic or inorganic), would be very unlikely. But, obviously, this theory helps explain bonding to plastics and to wood, albeit by subtly different detailed mechanisms.

Mechanical Theory of Adhesion. According to the mechanical theory of adhesion, for an adhesive to function properly it must penetrate the microscopic asperities (e.g., peaks and valleys, open pores, and crevices) on the surface of adherends, and displace any trapped air at the interface. Adhesion is thus believed to be the result of mechanical interlocking or anchoring of the adhesive to an adherend and, through the adhesive, of adherend to adherend. There is no need for any actual chemical bonding. The resulting mechanical interlocking is, without question, an important factor in bonding of many porous materials. Examples include open-celled rigid or elastomeric polymer foams, porous ceramics (e.g., stones, bricks, cement, and concrete), unglazed engineered ceramics, polymeric- and carbonaceous-matrix composites, wood, and even many metals that have a tenacious and porous native oxide or tarnish layer. In fact, it

is well known that adhesives generally bond better to abraded nonporous surfaces than to smooth surfaces, with abraded metals and etched glasses being good examples. For this reason, mechanical abrading and/or chemical etching is an important step in adhesive bonding for producing strong joints.

The actual effect of abrasion may be the result of several factors, including (1) enhancing mechanical interlocking or anchoring by roughening the surface; (2) creating a surface that is very clean and thus more wettable; (3) forming a highly chemically reactive surface; and (4) increasing the surface area of the bond interface due to the roughening produced. While the surface unquestionably is made rougher by abrasion, it is believed that a change in physical characteristics as well as chemical reactivity of the surface leads to an increase in adhesion. In any case, some degree of mechanical interlocking almost always contributes to an adhesive bond.

Adsorption Theory of Adhesion. A major theory of adhesion attributes the force of adhesion to the molecular contact and secondary bonding that occur between an adhesive and an adherend. The process of establishing intimate contact between the adhesive and an adherend is called "wetting." *Wetting* is the process in which a liquid spontaneously adheres to and spreads over the surface of a solid. The degree of wetting is controlled by the balance between the surface energy or surface tension of the liquid–solid interface versus the liquid–vapor and solid–vapor interfaces it replaces (see Chapter 9, Section 9.3.2). A surface is said to be completely wetted by a liquid when the liquid adheres and spreads to form an infinitely thin film (with a contact angle (θ) of 0 degrees), and is said to be totally non-wetted when the contact angle reaches 180 degrees and the liquid "beads" on the surface. The degree of wetting decreases in going from a contact angle of 0 degrees to about 90 degrees, with values over 70 degrees indicating poor wetting for most processes and purposes. For an adhesive to wet an adherend, it should have a surface energy (γ) lower than the adherend—the more so, the better.

Good wetting is considered to have occurred during adhesive bonding when the adhesive flows to fill the microscopic peaks and valleys and open pores on an adherend's surface (as shown in Figure 4.6a). Poor wetting (as shown in Figure 4.6b) is said to have occurred when the adhesive bridges over the valleys, resulting in a reduction of

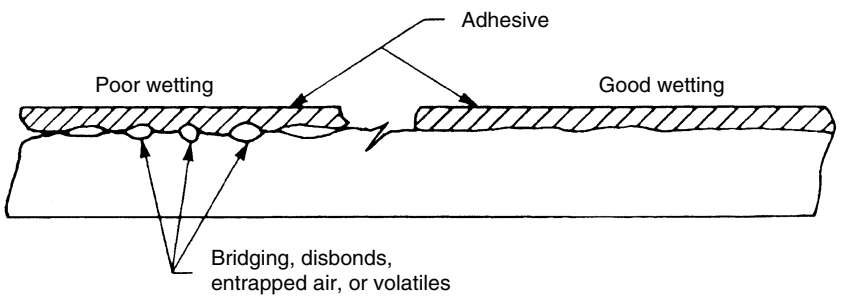

Figure 4.6 Schematic illustration of good (proper) and bad (improper) wetting of an adherend by an adhesive during bonding. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 4.2, page 113, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

the actual contact area between the adhesive and the adherend, thus lowering the overall joint strength.

After intimate contact has been achieved between an adhesive and an adherend through wetting, it is believed that permanent adhesion results primarily from the forces of chemical bonding. The chemical bonds involved in *adhesion* and *cohesion*[6] can be either primary (e.g., ionic, covalent, or metallic) but are usually secondary (e.g. van der Waal's bonds or, as found in cured cement, hydrogen bonds). Which type of bonding predominates depends on the chemical nature of the adhesive and the adherend. Secondary bonding from van der Waal's forces is undoubtedly the major contributor to the adsorption mechanism, except in cured cement or mortar, where hydrogen bonding occurs in the process of hydration.

4.3.4 Weak Boundary Layer Theory

In one of the first serious technical treatments of adhesion, Bikerman (1961) proposed that if an adhesive bond is properly made, the joint will fail in either the adhesive or one of the adherends, whichever has the lower cohesive strength (see footnote 6, Subsection 4.3.3). If an adhesive bond fails at a lower strength than expected for either of these, it does so because it failed through a weak boundary layer at the interface between the adhesive and one of the adherends. Thus, the common supposition that adhesive-bonded joints can fail at the bond interface (i.e., adhesively—see footnote 6, Subsection 4.3.3) is really incorrect. They are really failing, according to Bikerman and many others, through a weak layer of some kind immediately adjacent to the actual interface. Such layers can arise from some chemical event (e.g., a reaction) in the adhesive or in the adherend, possibly due to the environment.

The lesson from Bikerman's proposal is that every effort should be made during adherend surface preparation, adhesive preparation, adhesive application, curing, etc., to eliminate or prevent any weak boundary layer from forming and degrading the expected joint's performance. Some examples of sources of weak boundary layers are (1) concentration of low-molecular-weight constituents for organic-type adhesives or low-density constituents for inorganic types of adhesives due to separation during bonding; (2) weakly attached oxide or other tarnish layers on metals; (3) contamination of the adherend(s) by oil, grease, or adsorbed water (in some cases) due to improper cleaning; and (4) entrapped air at the interface.

Figure 4.7 schematically illustrates the four predominant mechanisms, theories, or rationalizations of adhesion, plus the concept or rationalization for poor adhesion arising from weak boundary layers.

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[6] *Adhesion* is the state in which two different materials are held together at their surfaces by physical or chemical valence forces, or both, such that it is necessary to do work to separate them. *Cohesion* is the state in which particles making up a single substance are held together by primary or secondary chemical valence forces.

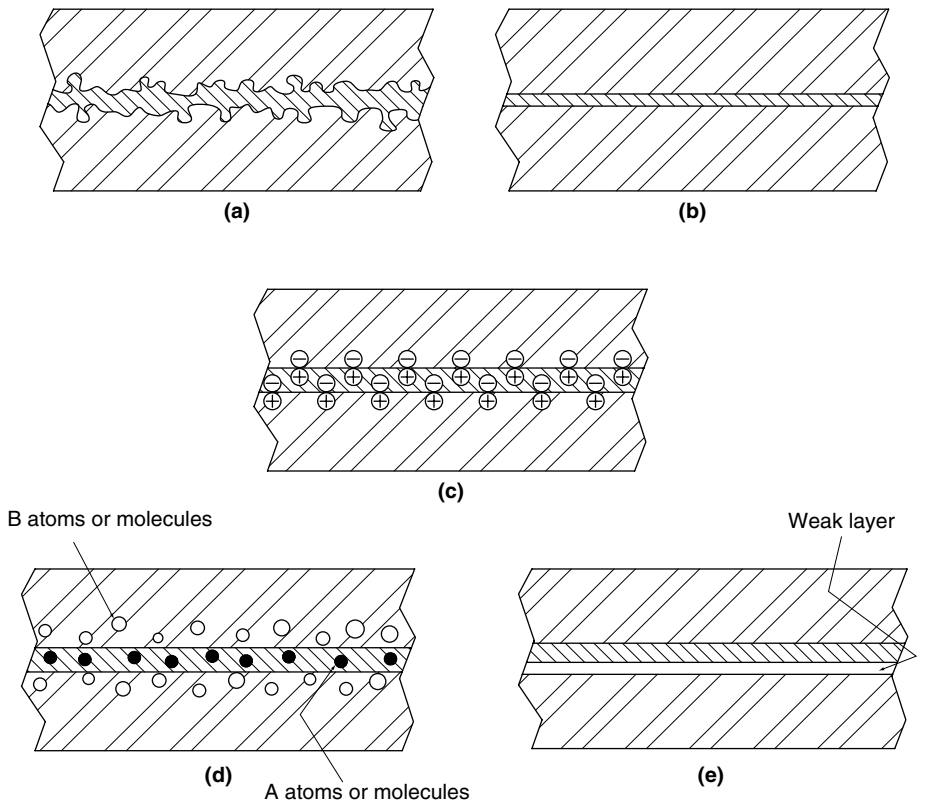


Figure 4.7 Schematic illustration of the various mechanisms that can lead to adhesion during adhesive bonding: (a) mechanical interlocking of adhesive into asperities; (b) secondary bonding from adsorption with proper wetting from surface-energy effects; (c) electrostatic attraction from charge separation; and (d) diffusion of atoms or molecules back and forth between adhesive and adherends. Also, (e) the formation of a weak boundary layer leads to the adhesive failure of joints.

4.3.5 Adhesive Tack and Stefan's Equation

An old, somewhat overlooked phenomenological explanation of adhesion appeared in J.J. Bikerman's classic work on adhesive bonding, *The Science of Adhesive Joints* (1961). The explanation is simply that—an explanation, not another theory as such. Bikerman explains adhesive bonding quite satisfactorily in terms of what he calls "tack," and he presents the development of an equation by Stefan that provides a useful qualitative understanding of how adhesives can be expected to behave, as well as an attempt to quantify the resulting joint strength. The explanation goes like this: When the gap between two substrates or adherends is filled with a liquid or, at least, a soft plastic solid (e.g., an adhesive), it takes work to separate the adherends again.

The resistance to separation is referred to as "tack" or "tackiness," as long as the intermediary (here, an adhesive) remains liquid or at least pliable. In its usual usage, *tack* or *tackiness* refers to the situation where the joint can be produced with the application of only a weak externally applied force and the measurement of the resistance to separation is made soon after the adhesive is applied. It is interesting to consider the properties necessary for development of tackiness or development of joint strength in an adhesive-bonded system.

One of the factors affecting tack is an initially low viscosity in the adhesive. This is because it is necessary for the adhesive to distribute over the joint area to create full contact by spreading under a squeezing force or with the application of work to the joint elements. However, the resistance to separation clearly increases as the viscosity of the adhesive increases thereafter. In other words, a low viscosity permits rapid establishment of tack, but the resulting joint strength is low. A high viscosity, on the other hand, would increase the joint strength but at the cost of greater difficulty in establishing tack. Practical adhesive systems seemingly require some compromise value of viscosity or require that the viscosity of the adhesive change (increase) with time after application.

The gradual establishment of good contact between a viscous liquid or plastic solid adhesive and a solid adherend has been widely studied. In most cases, the measure of good contact is judged from the resistance of the system to subsequent separation. It has been widely observed that this resistance generally increases with the time of contact t as well as with the pressure f used to produce contact. The product ft during squeezing out of the adhesive is equal to (for Newtonian adhesives) or proportional to (for non-Newtonian adhesives) the product ft during separation. This behavior is exemplified when a piece of rubber, for example, is cut in two and the two new surfaces are immediately pressed back together by a pressure f for a time t. Pulling apart these two pieces is more difficult the greater the values of f and t. Bikerman states that with polyisobutylene, the force needed to separate two 1-cm wide strips by peeling was 10^5 dynes/cm after 15 minutes of contact and 2.2×10^5 dynes/cm after 900 minutes (15 hours) of contact. Furthermore, after five minutes of contact, the peeling force was 5×10^4 dynes/cm when a contact pressure 5,000 dynes/cm^2 was applied and 18×10^4 dynes/cm when 60,000 *dynes*/cm^2 was applied. Indeed, after prolonged contact, the stress needed to separate the two pieces could equal the cohesive or internal breaking strength of the material, with the contact time required for this to occur being dependent on the particular rubber. In fact, most of us have experienced rubber that tears when we try to separate it after it has been under pressure for a long time.

The question remains as to the mechanism responsible for the resistance to separation. The most frequently cited example is that of Johannson blocks used in metrology or gauging. When two clean, dry blocks are pressed—or, more commonly "wrung"—together in air, the force needed to separate them is considerable. A common but erroneous explanation for the origin of this "bonding" force is the force needed to overcome atmospheric pressure due to the vacuum created between the blocks by squeezing out the air. Of course, no such vacuum occurs because Nature abhors a vacuum. Three other reasons for the attraction between the blocks are generally considered.

The first reason is that even though seemingly clean, the surfaces of the blocks (or any real materials) are actually contaminated by a liquid (e.g., an oil used to protect the blocks from corrosion, the oil from someone's hands, or water condensed from the atmosphere). As the blocks are neither microscopically smooth nor completely flat, they have ridges and valleys. Thus, contact occurs only at relatively high points rather than everywhere along the interface. This being the case, any trace of liquid between the blocks forms droplets around the microscopic points of contact, producing a meniscus at each contact point. If the radius of curvature of the meniscus is R, the capillary pressure in the droplet is given by γ/R, where γ is the surface tension of the particular liquid. The attractive force exerted by each such droplet is given by this pressure times the area of the point of contact, $\pi r^2\gamma/R$, where r is the radius of the point of contact. For a typical Johannson block, R is approximately 10^{-6} cm (i.e., the height of ridges or depths of valleys), γ for a typical liquid is 50 g/sec^2, and the radius of the point of contact is approximately 10^{-4} cm, so the attractive force for each point of contact is 1.5 dynes. For 1,000 contact points over a surface (which would not be many for a surface with ridges and valleys of the size given), the total force is 1,500 dynes. If the volume of liquid is great enough to allow the formation of a continuous film on the order of 10^{-6} cm thick, the attractive force would be 5×10^7 dynes/cm^2 of block surface. Quite a force!

The second reason for attraction assumes that no such liquid is present on the block surfaces. Instead, the blocks are said to be attracted because of electrostatic forces that exist in all materials. These electrostatic forces arise from the work function of a solid, which, in turn, arises from the chemical composition of the block, surface contaminants, the crystallographic orientations of the surface layers or surface grains, and internal stresses. This is related to the electrostatic theory of adhesion presented in Subsection 4.3.3.

The third reason for attraction is the predominant reason, and it relates to the tackiness of adhesives. Specifically, the product of the time and pressure used to press together two plates separated by a viscous adhesive leads to an equal product of time and pressure needed to separate them again by reversing the motion or work. This has been expressed in the "Stefan equation" as:

$$ft = \frac{3}{4}\,(\pi\eta a^4)(1/h_1^2 - h_2^2) \tag{4.1}$$

where f is the force required to separate the surfaces, t is the time required to separate the surfaces, η is the viscosity of the adhesive, a is the diameter or other linear dimension of the contact, h_1 is the initial clearance between adherends before pressing together, and h_2 is the final adhesive thickness.

For the typical case, where the adhesive layer is considerable thicker than the initial gap, Stefan's equation becomes:

$$ft = \frac{3}{4}\,(\eta)(a^2/h_1^2) \tag{4.2}$$

For Johannson blocks, Stefan's equation (in the simplified form of Equation 4.2) says that a 100-g block with $a = 2.55$ cm and a separation of $h = 10^{-6}$ cm (comparable to the height of asperities) would take 1.8×10^5 sec (50 hours) to separate in air (with its viscosity η of 1.8×10^{-4} g/cm-sec) under the force of gravity (f= approximately 10^5 gcm/sec^2). If a liquid adhesive filled the gap between two plates, the time to

separate these plates would be much longer. Water instead of air between the Johannson blocks would cause them to adhere together for 10^7 seconds (116 days), given the viscosity of water (i.e., $\eta = 0.01$ g/cm-sec).

The real significance of Stefan's equation is that it provides a very useful qualitative understanding of adhesive bonding. It predicts that adhesive bond strength will increase with the viscosity of the adhesive (η), with the area of bonding (a^2), with a^4, and with the thinness of the bond layer (h). This is consistent with observations or observed phenomena and is the basis for the formulation of adhesives and the design of joints for adhesive bonding. Adhesives are formulated to have a low initial viscosity to facilitate establishment of contact. They then increase in viscosity with time through evaporation of a solvent, the diffusion of a solvent or diluent (see Chapter 5, Section 5.2), the cross-linking of a thermosetting polymer, or the stiffening upon cooling of a thermoplastic polymer. Obviously, bond area and bond line thickness are also important to joint strength. Interestingly enough, no adherend properties appear anywhere in Stefan's equation, and thus it would seem not to affect bond strength.

4.4 FAILURE IN ADHESIVE-BONDED JOINTS

4.4.1 Modes of Failure and What They Indicate

Just as there appear to be many mechanisms that can operate singularly or in various combinations to produce strong adhesive-bonded joints, there are also several different mechanisms or modes by which an adhesive-bonded joint can fail. As with all failures, much can be learned about why the failure occurred in the first place by observing the mode by which failure took place. Two predominant mechanisms of failure in adhesively bonded joints are "adhesive failure" and "cohesive failure." *Adhesive failure* is interfacial failure between or seemingly between (but actually just adjacent to) the actual interface between the adhesive and one of the adherends. It tends to be indicative of a weak boundary layer (see Subsection 4.3.4), often due to improper preparation. *Cohesive failure* is when failure in the form of physical separation results in a layer of adhesive remaining on both adherend surfaces or, more rarely, when the adherend fails before the adhesive fails, with separation occurring totally within one of the adherends. This latter mechanism is known as "cohesive failure of the substrate." These different types of failure are shown schematically in Figure 4.8.

The ideal type of failure, as proposed by Bikerman (described in Subsection 4.3.4) is when cohesive failure occurs within the adhesive or one of the adherends, depending on what the designer would prefer. With this type of failure, the maximum strength of the materials comprising the joint has been reached, and there is no lingering question about improper preparation of the joint before bonding or of improper bonding procedures (see Section 4.5).

Joint failure in service or during testing is usually neither purely adhesive nor cohesive; it is usually a mixture of both modes. For this reason, the operative failure mode is often expressed as a percentage of cohesive or adhesive failure, with an ideal failure being 100% cohesive.

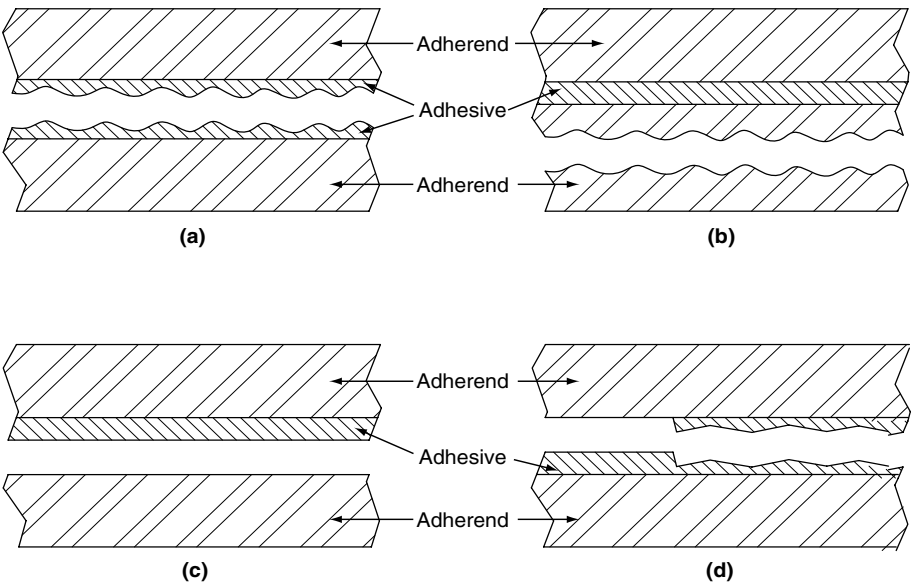


Figure 4.8 Schematic illustrations of two manifestations of *cohesive* failure, (a) cohesive failure within the adhesive and (b) cohesive failure within one of the adherends, versus (c) *adhesive* failure along the adhesive-adherend interface versus (d) *mixed-mode* failure in adhesive-bonded joints.

The mode of failure should not be the sole criterion for judging whether a particular adhesive-bonded joint was successful, however. Some combination of adhesive and adherends may fail adhesively but exhibit greater strength than a similar joint bonded with a weaker adhesive that fails cohesively. In practice, it is the ultimate strength of a joint, regardless of what process is used to make it, that is usually the more important measure of success than the mode of failure.

4.4.2 Causes of Premature Failure in Adhesively Bonded Joints

Premature failure of adhesively bonded joints (as well as any joint) is always a serious concern. The precise cause of premature failures in adhesively bonded joints is difficult to determine, however (much more difficult than for joints produced by other joining processes). For example, if the adhesive fails to wet the surface of one of the adherends completely during adhesive application, the bond is certainly less than optimal because bond area is less than expected in areas of no wetting. Also, adhesion is less than expected in areas where a weak boundary layer forms. Internal stresses arising from adhesive shrinkage during setting or curing, or stresses arising from different coefficients of thermal expansion (i.e., CTEs[7]), can cause premature failures.

[7] The effects of differential coefficients of thermal expansion (or CTEs) can be offset through the use of an inherently flexible adhesive or appropriate fillers added to the adhesive (see Chapter 5, Section 5.2).

Table 4.3 Major Causes of Failure in Adhesive-Bonded Joints

Adhesive is not compatible to adherend(s), leading to:
- failure of the adhesive to wet the adherend surface(s)
- adverse chemical reactions at the bonding interface(s)
Improper adherend preparation, leading to:
- incomplete wetting of the adherend by the adhesive
- void entrapment or gas (porosity) formation at bonding interface(s)
- weak boundary layers (e.g., oxides, tarnish, reaction zones) at bonding interface(s)
Internal stresses:
- arising from adhesive shrinkage
- arising from differential C.T.E.s between adherend and adhesive
Out-of-plane peel or cleavage loading arising from improper joint design
Processing errors:
- arising from improper adherend surface preparation
- arising from improper adhesive application (e.g, working time exceeded)
- arising from improper curing or setting
Operating environment leads to degradation of the adhesive or adhesive-adherend interface(s)

The type of stress acting on the completed bonds, their orientation relative to the adhesive layer, and their rate of stress application are also important factors influencing failure. Operating environmental factors such as temperature, moisture level (e.g., presence of water or humidity), salt or salt spray, organic solvents, and radiation can also seriously degrade the performance of adhesive-bonded joints.[8]

Whenever possible, candidate adhesive-bonding situations should be evaluated under simulated operating loads and environmental conditions. This includes adhesive composition and forms, joint geometry, and bonding practice (see Chapter 5, Section 5.7). A good test is worth thousands of words and hours of pondering.

Table 4.3 lists the major causes of failure in adhesive-bonded joints.

4.5 KEY REQUIREMENTS FOR QUALITY ADHESIVE BONDING

4.5.1 General Descriptions of Key Requirements

The objective of all structural adhesive bonding is to produce a bond that provides the maximum strength and quality possible for the particular combination of adhesive and adherends, usually at the minimum cost. To achieve this objective, several key requirements must be met, including (1) cleanliness of the adherend surfaces before adhesive application or bonding; (2) proper wetting of the adherends by the adhesive; (3) proper choice of adhesive for the particular adherend(s) and the prevailing service conditions; and (4) proper joint design for the types and magnitudes of expected loads. A further

[8] Combined factors such as unfavorable stress state and certain environmental conditions can be expected to produce a synergistic effect, often reducing joint strength more than might be expected.

requirement in the case where liquid adhesives are used is that the adhesive, once applied, must convert into a solid to produce joint strength in accordance with Stefan's equation.

The following subsections look briefly at each of these requirements.

4.5.2 Joint Cleanliness for Adhesive Bonding

In order to obtain a sound, strong adhesive bond it is essential to start with clean surfaces on the adherends. This is true because adhesive bonding is a surface phenomenon. Any and all foreign materials such as dirt, grease, cutting coolants and lubricants, ink or crayon marks, visible water (including dew, frost, and ice), obvious moisture (e.g., high humidity), and weak surface scales (e.g., oxides, sulfides, and other tarnishes) must be thoroughly removed. If they are not removed, the adhesive will either not be able to reach and wet the actual adherend surfaces or will bond to or form weak boundary layers, compromising the final joint strength.

Thorough cleaning with various mechanical, physical, or chemical processes, or some combination of these, removes weak boundary layers and mechanically, physically, and/or chemically conditions the adherend surfaces. The overall process of cleaning is often called "surface preparation" or "pretreatment" and usually involves one, two, or three of the following steps, in sequence, always starting at the first step and progressing to whatever step is felt necessary: (1) solvent cleaning; (2) intermediate chemical, physical, and/or mechanical cleaning; and (3) chemical treatment. A process called "priming" may also be carried out as a fourth step in some cases to ensure superior, durable bonds under particularly adverse environmental conditions.

Solvent cleaning is a process of removing soil from the surface of adherends using an organic solvent, without physically or chemically altering those adherends. Solvent cleaning can be an end in itself or it can be the preliminary step in a series of progressively more aggressive cleaning and treatment operations. Four basic solvent procedures that are progressively more vigorous are as follows:

1. Vapor degreasing for the removal of loose adhering particulate matter, dirt, or light soluble soils using hot solvent (e.g., trichloroethylene) vapor that condenses on the adherend and flows away debris.
2. Solvent wiping, immersion, or spraying with any of several different solvents (e.g., ethanol, methanol, acetone, or trichloroethylene) for the removal of light or heavy soluble soils (e.g., oils, greases, waxes), dirt, and particulate matter.
3. Ultrasonic vapor degreasing for the removal of more tenacious soil and insolubles through the scrubbing action of collapsing bubbles (i.e., cavitation) arising from ultrasonic excitation of a liquid solvent.
4. Ultrasonic cleaning in solvent, using the scrubbing action of collapsing bubbles during solvent immersion to break loose tenacious contaminants, followed by a liquid solvent rinse to remove residues. Organic solvents are not necessary. Aqueous solutions with surfactants, detergents, or alkaline or acid cleaners can be used. This process produces high-quality cleaning but is not as efficient as vapor-cleaning processes.

Following solvent cleaning, intermediate cleaning is often needed to remove especially tenacious contaminants or loosely adhering layers of scale. Intermediate cleaning is a process of removing soil or scale from an adherend surface with physical, mechanical, or chemical means, singly or in combination, without altering the adherend chemically. These cleaning methods are aggressive enough that they may remove some small amounts of the parent material. Some examples of widely used and acceptable mechanically based intermediate cleaning methods are grit blasting, wire brushing, sanding, abrasive scrubbing, or scraping or filing. Some examples of physically based methods are electrical corona discharge and various high-speed ablative processes using flames, plasmas, or lasers. Examples of chemically based methods are alkaline, acid, and detergent cleaning (often with scrubbing). An intermediate step in cleaning should always be preceded by solvent cleaning but may be the last step required for adequate surface preparation before bonding.

Chemical treatment is the process of treating a clean adherend surface by chemical means, with the objective of changing the surface of the adherend chemically to improve its adhesion qualities. The most common chemical treatment is acid or alkaline etching (''pickling'') to remove especially tenacious surface films (e.g., oxides) or smeared surface (adherend) material, or to roughen the surface on a microscopic scale. Solvent cleaning should always be performed before chemical treatment; frequently, intermediate cleaning should be performed as well.

Besides physically roughening the surface of the adherends microscopically to enhance mechanical anchoring, chemical treatment often activates the surface to better accept the adhesive. The mechanism for activation is the removal of adsorbed gases, intervening oxides, or other scales, and the exposure of atomically clean material.

Occasionally, after these cleaning operations have been performed, the surface of an adherend is subjected to ''priming.'' *Priming* involves applying a dilute solution of the adhesive's active bonding agent in a suitable organic solvent to the surface of the adherend to produce a dried film thickness of 0.0015–0.05 mm (0.00006–0.002 in.). This film protects the adherend from oxidation after cleaning, improves wetting, helps to prevent corrosion, helps to prevent adhesive peeling, and serves as a barrier layer to prevent undesirable reactions between the adhesive and the adherend. It also tends to help hold the adhesive in place during assembly for bonding. Sometimes primers consist of special ''coupling agents'' that have an affinity for the adhesive and the adherend(s).

Table 4.4 lists methods of cleaning and pretreating adherends for generic adhesive bonding, as opposed to those specific to particular adherends.

4.5.3 Ensuring Wetting for Adhesive Bonding

As stated earlier, wetting is important in adhesive bonding[9] because it increases the contact area between the adhesive and the adherends over which the forces of adhesion

[9] In fact, wetting is important to all joining processes that rely on the development of bonding forces at surfaces, which is absolutely the case with brazing (Chapter 8) and soldering (Chapter 9). It is also the case for certain types of welding processes involving transient liquid phases (Chapter 6).

Table 4.4 Methods of Cleaning for Adhesive Bonding

Solvent Cleaning—to remove light, soluble surface contaminants by
- vapor degreasing
- solvent wiping, immersion, or spraying
- ultrasonic-assisted vapor degreasing
- ultrasonic-assisted solvent immersion
Intermediate Chemical Cleaning—to remove tenacious contaminants or loosely adhering layers of tarnish or scale by
- detergent cleaning
- alkaline cleaning (e.g., sodium hydroxide)
- acid cleaning or "pickling" (e.g., hydrochloric acid, nitric acid, aqua regia)
Intermediate Mechanical Cleaning—to remove tenacious tarnish or scale and/or roughen the adherend surface(s) to improve adhesive gripping by
- wire brushing
- adhesive scrubbing
- grit blasting
- sanding
- scraping or filing
Intermediate Physical Cleaning—to remove contaminants and/or activate the adherend surface(s) to facilitate chemical bonding by
- electrical corona discharge
- flame, plasma, or laser ablation
Chemical Treatment—to produce a surface on the adherend(s) that better accepts the adhesive by
- surface chemical conversion processes for metal (e.g., anodizing of Al)
- application of a dilute solution of the active agent in the adhesive as a primer

act. For good wetting by the adhesive, the surface(s) of the adherend(s) must be properly and thoroughly cleaned as described in the preceding subsection. For proper bonding, the effectiveness of wetting must be assessed, at least as part of some quality assurance plan and procedure, by either of two popular tests. The first is the "water-break test" and the second is the "contact angle test." Both tend to be conducted during the establishment of a standardized process for use in production, as part of then-imposed process control.

In the *water break-free test*, cleaned (and possibly pretreated) adherends exactly like those to be used in production are immersed in water, lifted from the water, and observed to see that a continuous, unbroken film of water adheres to the intended bonding surfaces for some time. The appearance of break spots or "islanding" indicates poor wetting in those areas. A continuous film, on the other hand, indicates good wetting. While the test is strictly qualitative, it gives a good indication of suitability for subsequent adhesive bonding. As a practical matter, this test could be conducted by observing actual parts to be bonded as they are removed from a final clean water rinse just prior to adhesive application, if production or construction logistics permit.

In the *contact angle test,* the angle of contact between the liquid or pliable solid adhesive and adherend(s) at the point where they come together is actually measured,

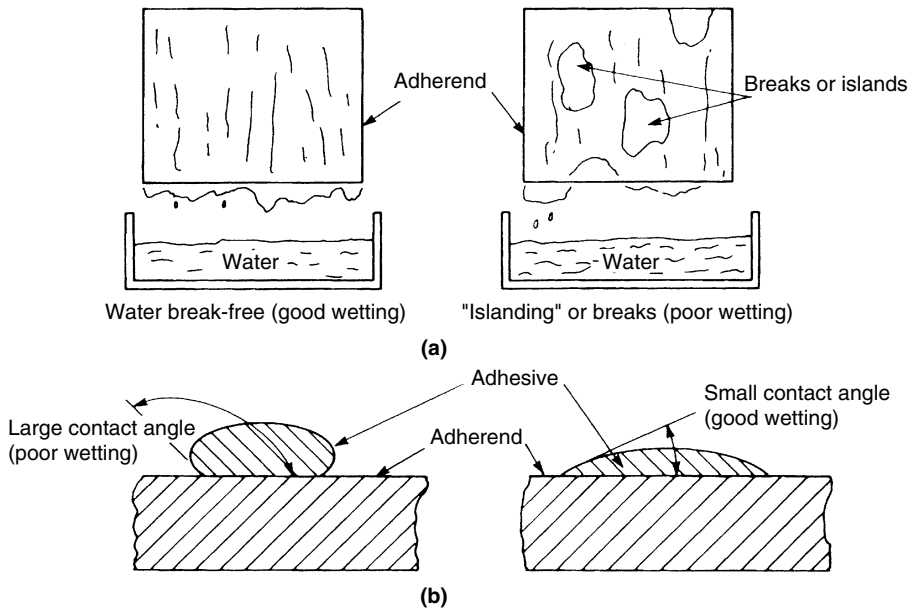


Figure 4.9 Schematic illustration showing (a) water break-free test and (b) contact angle measurement methods for assessing wetting. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 4.5, page 122, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

usually using an optical comparator that shows objects in shadow-profile under uniform, directed lighting. Smaller contact angles indicate better wetting, with angles over about 70 degrees indicating difficulty with wetting. This test is more quantitative, but it is impractical to conduct as a step in product manufacturing and is of relatively little consequence.

Figure 4.9 shows schematically how wetting can be assessed with each of these above tests.

4.5.4 Selecting an Adhesive

Assuming that joint cleaning, any pretreatment, and wetting assessment have been done properly, successful adhesive bonding is ultimately the result of selecting the proper adhesive. Table 4.5, taken and adapted from Landrock's *Adhesives Technology Handbook* (1985), gives an excellent summary of the factors that influence adhesive selection. These factors include (1) capability for bonding specific adherends and adherend combinations (which really means having the appropriate chemical properties to allow one or more of electrostatic attraction, interdiffusion, or adsorption to occur); (2) suitability to service loading requirements (e.g., tension, shear, peel, impact, fatigue), chemical factors (e.g., attack by external chemical agents or solvents, or

Table 4.5 Factors Influencing Adhesive Selection

Material Requirements:
- Compatibility with the adherend material(s) to be joined
- Inherent strength and elasticity properties of the adhesive
- Specialized functional properties of the adhesive system (e.g., electrical or thermal conductivity or insulation)
Service Requirements:
- Loading (stress) type (e.g., pure versus cleavage tension, pure shear versus peel)
- Internal chemical reactions in the adhesive or between the adhesive and adherend
- External chemical attack by solvents, chemical agents, etc.
Environmental Factors:
- Temperature extremes
- Moisture
- Weathering (i.e., cyclic temperature, humidity, and light)
- Radiation (e.g., UV light, gamma rays, cosmic rays, thermal neutrons, etc.)
- Oxidation
- Salt and salt spray
- Biological agents (e.g., molds, mildew, fungi, bacteria, rodents, vermin)
Production Requirements:
- Adhesive storage and storage stability
- Application requirements and methods
- Bonding range (e.g., temperature, humidity)
- Blocking or masking
- Working life
- Coverage
- Curing conditions (e.g., time versus temperature)
- Handling and disposal (see Health and Safety Requirements, below)
Cost:
- Inherent cost of adhesive
- Cost associated with application and curing
Health and Safety Requirements:
- Handling and exposure hazards to workers
- Handling and exposure (e.g., inhalation, ingestion) hazards to users
- Disposal

undesirable reactions between the adhesive and the adherend); (3) suitability for the service environment; (4) meeting specialized functional requirements (e.g., thermal or electrical insulation or conductivity, retained flexibility); (5) meeting production requirements (e.g., application requirements, working life, curing requirements), including (especially!) suitability for use on site in construction applications; (6) having acceptable cost for the perceived value of the application; and (7) posing no unmanageable health or safety hazards. These factors will be discussed in more detail in Chapter 5, Sections 5.4, 5.5, and 5.6.

One additional essential consideration in selecting an adhesive for any application is that the adhesive be capable of solidifying or stiffening after application in the liquid

or soft, pliable state. This consideration is based on Stefan's findings that low viscosity contributes to ease of adhesive application, while high viscosity leads to high bond strength (Subsection 4.3.5). The ways in which liquid adhesives are converted to solids and soft, pliable solid adhesives tend to become more hard and stiff are (1) through a chemical reaction (often cross-linking in thermosetting-type organic adhesives) induced by (a) heat, (b) pressure, (c) absence of air, (d) presence of water, or (e) use of a catalyzing curing agent, singly or in combination; (2) by cooling and solidifying by a phase change, or cooling to below a glass transition temperature without a phase change; and (3) by drying after the evaporation or absorption of any carrier solvent.

4.5.5 Proper Joint Design for Adhesive Bonding

One of the principal causes of a failure in adhesive applications is poor engineering design of the bonded assemblies or structures and their joints. Joints for adhesive bonding are not joints for mechanical fastening or welding. They have their own unique requirements and so should be designed to take advantage of the desirable characteristics and properties of adhesives while minimizing shortcomings. This requires consideration of the following: (1) providing the maximum bonding area possible in the design to help spread the applied load and minimize stress in the adhesive; (2) designing the joint in such a way as to force loads to be transmitted to the joint in favorable loading directions (e.g., pure compression, pure tension, or—most achievable—pure shear) (see Subsection 4.6.2); (3) orienting joints or designing joint elements or reinforcements in such a way as to minimize unfavorable out-of-plane (i.e., peel or cleavage) loading; (4) designing joints to ensure uniformity in thickness of the adhesive layer and keeping this layer as thin as practical to maximize tensile and shear strengths (see Subsection 4.6.4); (5) designing joints and their elements in such a way that volatile components of the adhesive can be expelled or absorbed by the adherends; (6) designing joints from combinations of materials that will minimize stresses arising from differences in coefficients of thermal expansion (especially for hard brittle adhesives, such as many of the inorganic types, including cements and mortars); and (7) designing joint elements and assemblies in such a way as to facilitate adhesive application, curing, and inspection. Joint design is considered in detail in the next section.

4.6 ADHESIVE JOINT DESIGNS, DESIGN CRITERIA, AND ANALYSIS

4.6.1 Basic Principles in Adhesive Joint Design

Joints intended to be adhesive bonded must be designed specifically for the use of adhesives, just as joints intended to be mechanically fastened or welded should be designed specifically for mechanical fastening or welding, respectively. This may seem obvious, but based on many unfortunate failures it seems to be forgotten too often. The aim of good adhesive-bonded joint design is to obtain the maximum strength for a

given area of bond for structural efficiency. In designing joints specifically for adhesive bonding, the basic characteristics of adhesives dictate the design of the joint, although adherend characteristics also play an important part (even though they do not appear anywhere in Stefan's equation in Subsection 4.3.5). This will be shown in Subsection 4.6.3. Most importantly, adhesive bonds act over areas rather than at single points, just as mechanical fasteners and most integral mechanical attachments do, so joints should be designed with the objective of minimizing the concentration of stress and maximizing the bonding area in any way possible.

Besides the obvious performance criteria, the selection of a joint design is also inevitably influenced by limitations in production (or, even more so, construction facilities), production cost constraints, and desired final appearance of the part or assembly.

The strength of an adhesive-bonded joint is determined primarily by the following factors: (1) the mechanical properties of the adhesive and the adherend(s); (2) presence of any residual (internal) stresses generated during processing; (3) the degree of true interfacial contact achieved through adhesive application and wetting; (4) the type of loading to which the joint will be subjected; and (5) the joint geometry.

The properties of specific adhesives and adherends will be discussed in Chapter 5 and in various subsequent chapters, respectively. The effect of residual stresses generated during processing is generally beyond the scope of this particular treatment, although sources of such stresses will be described. The degree of true interfacial contact was addressed in Subsection 4.5.3. The following subsections address the types of loading to which joints can be exposed, typical joint designs, joint design criteria, analysis methods and difficulties, and methods for improving joint efficiency.

Figure 4.10 shows some typical structural joints used with modern adhesive bonding.

4.6.2 Types of Stress Acting on an Adhesive-Bonded Joint

Five types of stress are typically found in adhesive bonded joints, as shown in Figure 4.11. They are, from most favorable to least desirable (1) pure compression, (2) pure shear, (3) pure tension, (4) cleavage, and (5) peel. These types of stress can occur singly or in any combination. Even when joints are stressed primarily in compression or tension or shear,[10] it will be seen that these stresses can produce peel or cleavage. Each type of stress is described briefly below.

Pure compression or compressive loading occurs when the applied load is perpendicular to the plane of a joint and tends to squeeze the joint closed. Not surprisingly, an adhesive-bonded joint is least likely to fail under this type of loading because it could be questioned why an adhesive is even needed (as the joint would not try to come apart anyway!). The one exception could be if the adhesive was considerably less tolerant of compression than the adherends, in which case the adhesive could

[10] In fact, while loading can actually be in shear, compression and tension can also give rise to shear by being resolved (as vectors) onto shear planes.

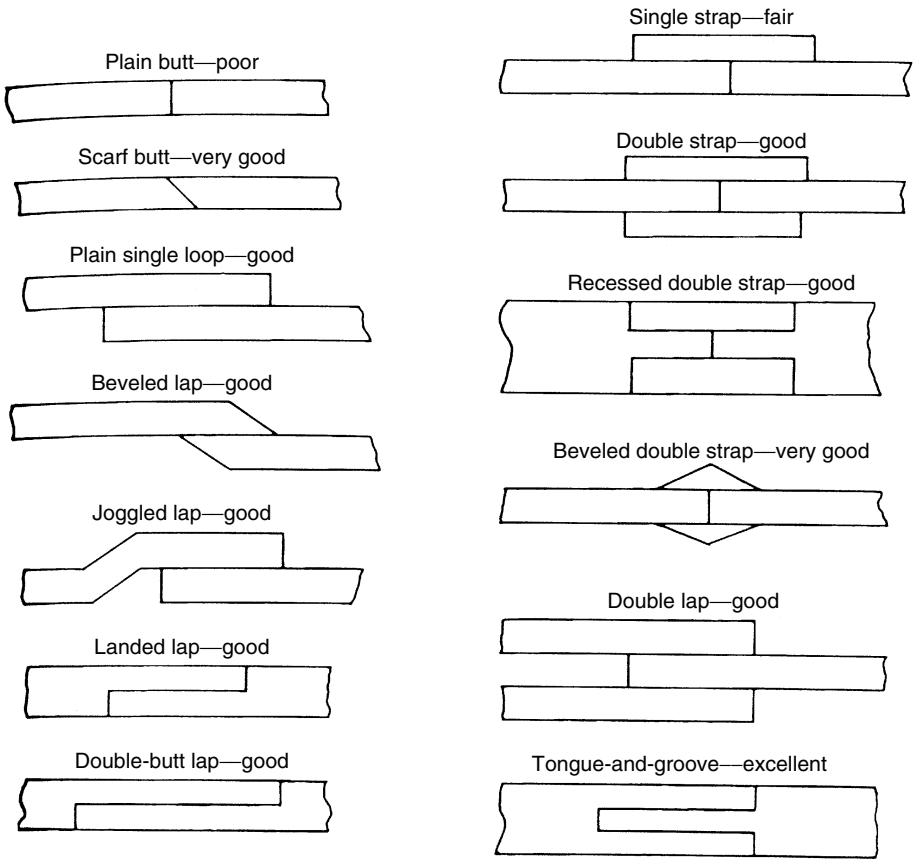


Figure 4.10 Schematic illustrations of typical examples of various structural joints in modern adhesive bonding. (Reprinted from *Adhesives Technology Handbook*, A.H. Landrock, Fig. 4.7, page 34, Noyes Publications, Park Ridge, NJ, 1985, with permission of William Andrew Publishing, Norwich, NY.)

fail by compressive fracture well before the adherends would fail by compressive fracture. Unfortunately, such loading (especially in the pure state) is rarely found in practice. Almost always, some out-of-plane load can occur that can lead to bending and, hence, peel or cleavage (e.g., a wind load on a vertical wall).

Although not next in the list of five stresses, pure tension or tensile loading is most appropriate to describe next. This type of loading also acts perpendicular to the plane of the joint but tries to open (rather than close) the joint, pulling the two adherends apart. In theory, under pure tension loading the stresses on the surfaces of the adherends and in the adhesive are evenly distributed. In reality, offsets in the joint, bending of the adherends, and other complications cause the actual loading and stress distribution to be nonuniform, leading to peel or cleavage. The strength of a

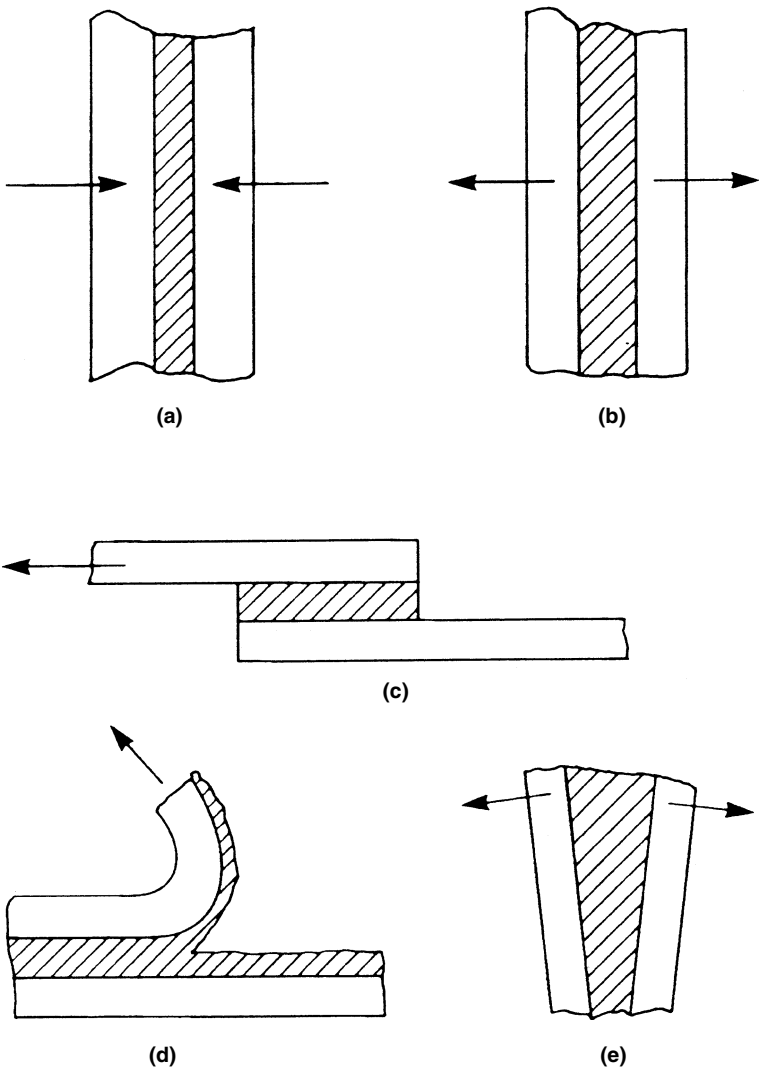


Figure 4.11 Schematic illustration of the various types of loading and stress that can act on adhesive-bonded joints, including (a) pure compression; (b) pure shear; (c) pure tension; (d) peel; and (e) cleavage. (Reprinted from *Adhesives Technology Handbook*, A.H. Landrock, Fig. 3.1, page 32, Noyes Publications, Park Ridge, NJ, 1985, with permission of William Andrew Publishing, Norwich, NY.)

tension-loaded joint should be comparable to a shear-loaded joint, barring complications, and can in a few cases exceed it. In tension joints, the adherends should be thick to avoid deflection or bending and offset loading.

The most common type of loading found in most adhesive-bonded joints is shear. In pure shear, loading is parallel to the plane of the joint and tries to separate the joint

elements by sliding them past one another. Pure shear imposes a uniform stress across the entire bonded area, thereby using the entire joint area to carry the applied loads to the best advantage. Whenever possible, most of the loading applied to an adhesive-bonded structure should be transmitted through the bonded joint(s) in shear. To accomplish this, joints commonly have a lapped or overlapped geometry (as described in the next subsection). Lap shear strengths are directly proportional to the extent (or length) of the overlap, but the unit strength actually decreases with the width of the overlap. The optimum shear strength of a bonded joint is largely dependent on the shear modulus of the adhesive and its optimum thickness. This thickness varies from 0.005 mm (0.002 in.) for high-modulus (i.e., stiff) adhesives to 0.015 mm (0.006 in.) for low-modulus (i.e., flexible) adhesives. The reason that adhesive thickness (the so-called "bond line") is best kept thin is that, presuming there is good adhesion between the adhesive and the adherends (at least for adherends that are inherently stiffer and stronger than the adhesive), the adherends actually act to reinforce the adhesive, causing it to act stiffer and stronger.

Again, while not next in the list, peel loading is definitely next in frequency of occurrence. This type of loading is out of the plane of the joint and tries to open the joint nonuniformly, virtually always from an edge because of the effects described in Subsection 4.6.4. For this type of loading to occur, one or both of the adherends must be flexible and able to deflect. When this is so, a very high stress develops locally at the adhesive–adherend interface. Peel-type loading, as we all know from our practical experience with adhesive tapes, is the way one removes the tape. This should be avoided wherever and however possible.

Cleavage loading is similar to peel loading, except that it forces one end of a bonded rigid (as opposed to flexible) assembly or structure to split apart. Cleavage occurs when an offset tensile force or moment is applied, causing stress to be non-uniformly distributed. Like peel, cleavage loading should also be avoided if possible.

4.6.3 Typical Joint Designs for Adhesive Bonding

The ideal adhesive-bonded joint is one in which, under all practical loading conditions, the adhesive is stressed in the direction in which it best resists failure (i.e., shear). Practical adhesive-bonded joints are designed with and used in many different configurations to achieve this objective, but the most common, as shown before, are illustrated schematically in Figure 4.10. The relative uses of these various joint types depend primarily on the load intensity to be achieved, as shown in Figure 4.12. As a general rule, as often cited in an old adage, "Simpler is always better." As it pertains to adhesive-bonded joints, simpler-looking joints are less costly and work well with simple, low-level loads, while higher, more complex loading situations demand more elaborate and expensive joint designs.

As a caution, butt joints cannot withstand bending loads because this leads to the development of cleavage forces and stresses in the adhesive. Lap joints are the most commonly used in adhesive-bonded joints, as they are simple to make in terms of both joint element fabrication and assembly, they can be used with thin adherends to minimize

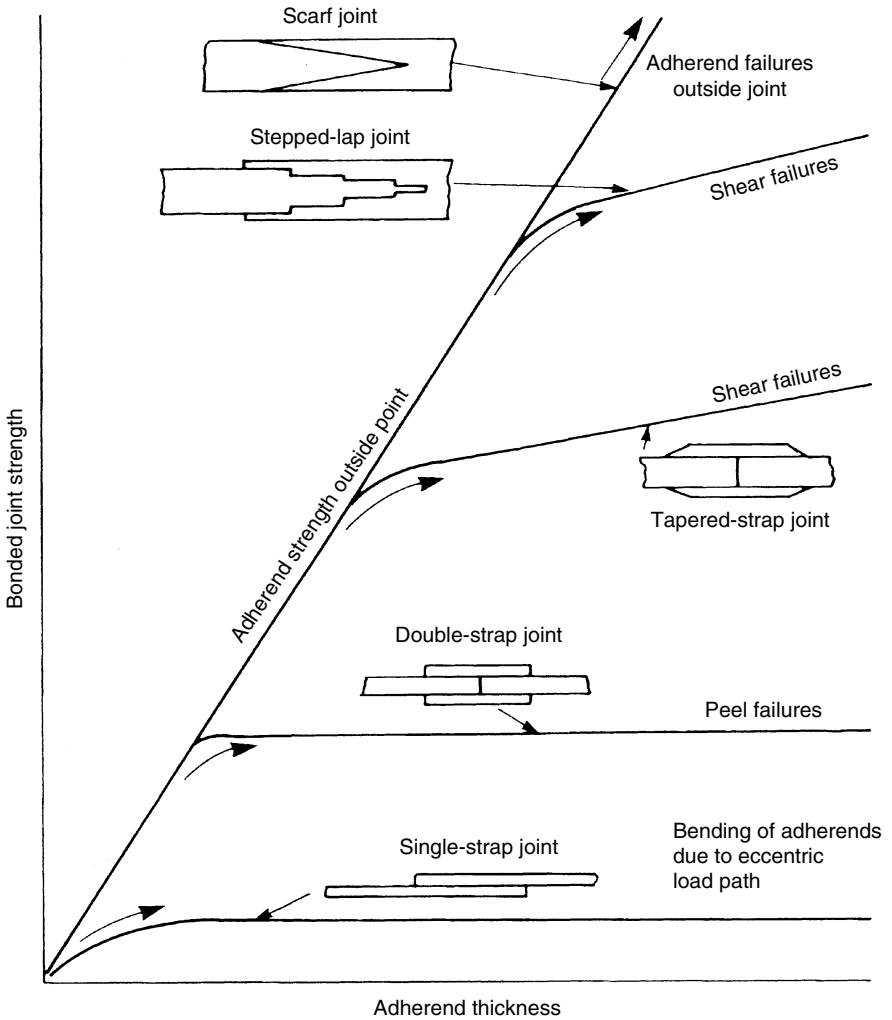


Figure 4.12 Schematic plot of joint type versus load intensity. (Reprinted from "Design of Adhesively Bonded Joints," L.J. Hart-Smith, Fig. 2, page 274. In *Joining Technologies for the 1990s*, J.D. Buckley and B.A. Stein, Eds., Noyes Data Corporation, Park Ridge, NJ, 1986, with permission of William Andrew Publishing, Norwich, NY.)

structural weight, and the stress developed in the adhesive is almost always shear. Unfortunately, bending can easily arise in simple lap joints, leading to cleavage.[11]

As a final consideration, if adherends are too thick to consider lap joint configurations, modified butt joints (e.g., scarf joints or tongue-and-groove joints) can be evaluated. Obviously, no good purpose is served by using unnecessarily complex joint configurations for lower load intensities. Conversely, it is hopeless to expect

[11] Methods for improving the efficiency of lap joints are presented in Subsection 4.6.6.

that simpler and cheaper configurations could ever sustain high-intensity and/or complex loads.

4.6.4 Classical and Modern Adhesive Joint Analysis

Aside from the various shortcomings associated with adhesive bonding listed in Table 4.2, some of the major hindrances to wider applications of this joining process include (1) defining the strength of a joint and comparing the quality of joints; (2) predicting joint strength; and (3) optimizing a joint's strength and reliability by altering its geometry. These problems are mechanical in nature and relate to the ability of anyone (including the average engineer) to perform stress analysis on adhesive bonded joints. The analysis, as will be described shortly, is complex in its own right. But to make matters worse, the subject of adhesive bonding is totally missing from most modern engineering curricula. Without engineers who work as designers knowing how to analyze adhesive-bonded joints, the likelihood of finding adhesive-bonded joints in more and more demanding or more critical applications is rightfully low.

The analysis required to properly design joints for adhesive bonding is complex for many reasons. First, adhesive-bonded joints rarely see simple loading and virtually never see pure loading of any type (e.g., compression, shear, or tension). Rather, they are usually subjected to some bending, with profound effects—the most serious of which is the development of out-of-plane peel or cleavage stresses. Second, none of the components of a real adhesive-bonded joint is completely rigid. In fact, the adhesive is usually chosen to be relatively flexible compared to the adherends to accommodate fit-up errors, impart damage tolerance for structural applications, and to gain secondary benefits of sealing and vibration damping. Furthermore, adherends may flex if they are thin or may act rigidly if they are thick, but they are never perfectly rigid. This lack of joint rigidity (or, contrarily, the relative flexibility in both components of a joint) has pronounced effects on the distribution of stress within the joint. Third, the thickness of the adhesive (as well as its modulus) affects distortion under loading and, thus, stress distribution in the joint. Finally, by their very nature, most adhesive-bonded joints are bi-material systems, often with very different properties, especially strain behaviors, between the two components (i.e., adhesive and adherends).

For these reasons, rigorous analysis of stress distributions and concentrations in adhesive-bonded joints is rare, even in this age of powerful computers and sophisticated modeling techniques. Nevertheless, two particularly important and widely used joints began to be analyzed extensively in the late 1930s, and the results have been checked and validated by laboratory tests and actual service experience. These two types are "lap" and "scarf" joints. Results for these simple joints have been extended to more complex joints using more sophisticated analytical and numerical techniques. The classical work of Perry (1958) on joint stresses will be presented first, followed by the remarkably insightful classical analysis by Volkerson (1938) explaining the origin of stress concentration. Finally, the more rigorous analytical work of Goland and Reissner (1944) on joint bending and resulting stress distribution will be presented.

Because of the complexity of the entire subject of joint analysis for adhesive bonding, the interested reader is referred to the original works (see the cited references section).

Table 4.6 includes schematic illustrations of the six most common lap and scarf joints for which stress distributions and concentrations were calculated long ago (Perry, 1958). These types include (1) co-linear scarf joints, (2) butt joints, (3) single flat offset lap joints, (4) double flat lap joints, (5) tubular lap joints, and (6) landed lap joints.

A pure scarf joint is the most efficient of the common structural joints and is the simplest to analyze because loading is co-linear and no bending is introduced. For such joints, the most important stresses are (1) the tensile stress that acts normal to the adherend faces trying to pull the adherends apart and (2) the shear stress that acts parallel to these faces trying to slide the adherends apart. Since the adhesive line in a scarf joint is at an angle to the applied loads, combined stress theory will give the modified angle functions for calculating these key stresses. Table 4.6 gives modified equations by Perry (1958) for calculating each stress, assuming the adherends involved in the joint are both the same material and isotropic, both of which are potentially very limiting assumptions. Since both stresses depend on sin θ, by designing with a small scarf angle θ, the joint strength depends only on adherend strength.

Stresses in butt joints can be determined from the equations for scarf joints by making the scarf angle $\theta = 90^\circ$. Butt joints fail to take advantage of the full strength of the adherends because the bond area is minimized, but, as with scarf joints, stress concentration is low.

The more complex joint configurations involve much more complicated analysis. The simplest and earliest of these considered the adherends in a single flat offset lap joint to be completely rigid and had the adhesive deform only in pure shear. As shown in Figure 4.13a, if the width of the joint is *b,* the length *l,* and the load *F,* then the shear stress τ is uniform and given by:

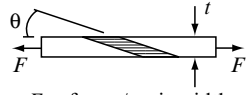
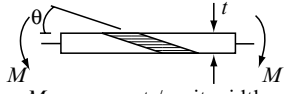
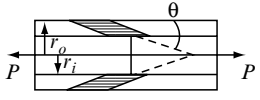
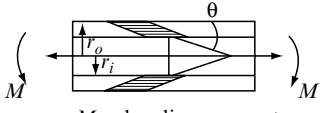
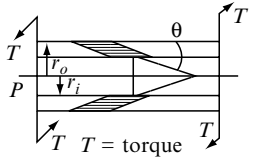
$$\tau = F/bl \tag{4.3}$$

If, on the other hand, the adherends are elastic (as shown in Figure 4.13b), the situation is quite different. For the upper adherend, the tensile strain at the end of the overlap is lowest and increased farther and farther from this end. For the lower adherend, there is a similar behavior, but going in the direction opposite from the joint. Thus, assuming that the adhesive–adherend interface remains intact, the uniformly sheared parallelograms in Figure 4.13a become distorted to the shapes shown in Figure 4.13b, leading to differential shear. It should be apparent from the shear in the upper and lower adherends that the stress in the joint and adhesive peaks at each end of the overlap.

The problem of non-rigid adherends was first analyzed in 1938 by Volkerson. In his "shear lag analysis," he assumed that the adhesive deformed only in shear while the adherends deformed only in tension. The solution is complicated and the details of the analysis are beyond the scope of this book, and so they are left to the interested reader by reference to Volkerson's original paper (1938, in German) or other sources (Anderson, 1977; Adams, 1984). The solution predicts, however, that the maximum shear stress in the adhesive occurs at the ends of the lap–joint overlap and is given by:

$$\tau_{max}/\tau_{mean} = (P/2)^{1/2} \coth (P/2)^{1/2} \tag{4.4}$$

Table 4.6 Summary of Equations for Analysis of Various Adhesive Scarf Joints

Type	*Loading*	*Geometry*	*Shear Stress*	*Normal Stress*
Flat Scarf				
	Tension, compression	 F = force / unit width	$\tau = \frac{F}{t} \sin\theta \cos\theta$	$\sigma = \frac{F}{t} \sin^2\theta$
	Pure bending	 M = moment / unit width	$\tau = \frac{6M}{t^2} \sin\theta \cos\theta$	$\sigma = \frac{6M}{t^2} \sin^2\theta$
Tubular Scarf				
	Tension, compression	 P = axial force	$\tau = \frac{P}{2\pi r_o t} \sin\theta \cos\theta$	$\sigma = \frac{P}{2\pi r_o t} \sin^2\theta$
	Pure bending	 M = bending moment	$\tau = \frac{2M(r_o + r_i)}{\pi(r_o^4 - r_i^4)} \sin\theta \cos\theta$	$\sigma = \frac{2M(r_o + r_i)}{\pi(r_o^4 - r_i^4)} \sin^2\theta$
	Pure torsion	 T = torque	$\tau = \frac{2T \sin\theta}{\pi(r_o - r_i)^2}$	$\sigma = 0$

Reprinted with permission from H.A Perry, "How to Calculate Stresses in Adhesive Joints," Production Engineering, Vol. 29, No. 27, 1958.

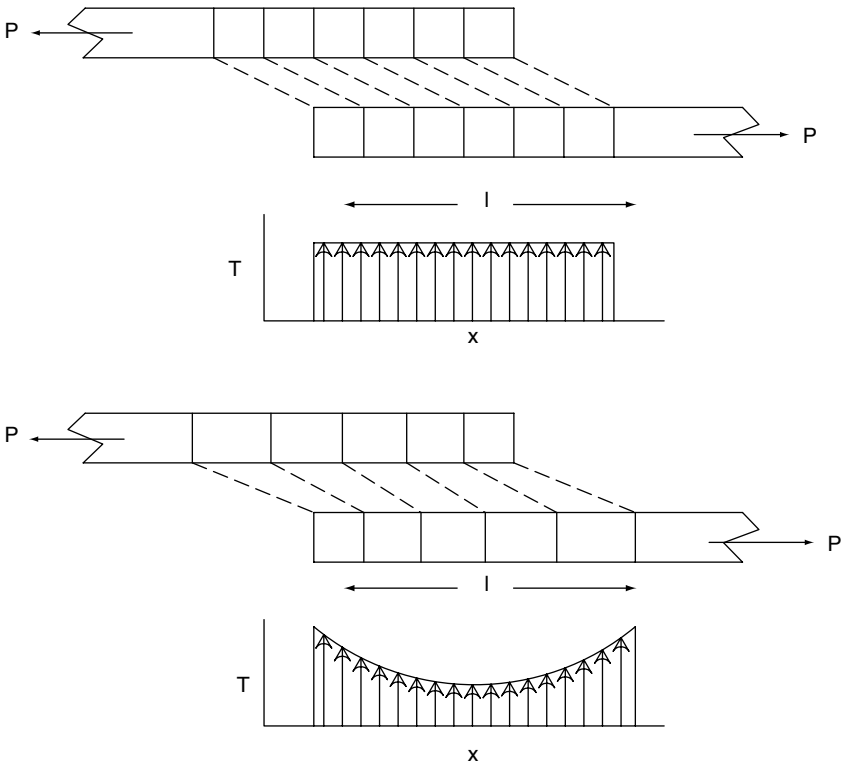


Figure 4.13 Schematic illustration showing the effect of "shear lag" in adhesive-bonded joints. (Adapted from "Theoretical Stress Analysis of Adhesively Bonded Joints," R.D. Adams, Fig. 1, page 189. In *Joining Technologies for the 1990s,* J.D. Buckley and B.A. Stein, Eds., Noyes Data Corporation, Park Ridge, NJ, 1986, with permission of William Andrew Publishing, Norwich, NY.)

where τ_{mean} is the mean (or average) applied shear stress ($= F/bl$), from Equation 4.3, and P is given by:

$$P = Gl^2/Et_1t_2 \tag{4.5}$$

where G is the shear modulus of the adhesive, l is the length of the joint or the overlap, E is Young's (tensile) modulus for the adherends (assumed to be the same!), t_1 is the thickness of the adherends (also assumed to be the same!), and t_2 is the thickness of the adhesive.

Illustrative Example 4.1—Determining Maximum to Mean Shear Stress in a Bonded Joint.

For the single flat lap joint shown in Figure IE 4.1, what is the ratio of the maximum shear stress to the mean or average shear stress? Assume that the modulus of elasticity for an aluminum alloy adherend is 72 GPa (10.5×10^6 psi) and the shear modulus for an epoxy adhesive is 2,464 MPa (360,000 psi).

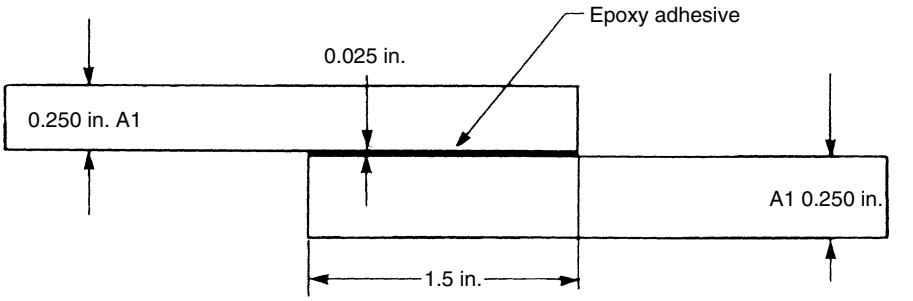


Figure IE 4.1 Schematic of a fully dimensioned simple single flat overlap joint. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 4.11, page 133, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

Using Equation 4.5 and substituting the values of shear modulus for the epoxy adhesive (360,000 psi), the length of overlap of the joint ($l = 1.5$ in.), the modulus of elasticity for the aluminum alloy adherends ($E = 10,500,000$ psi), and the thickness of the adherend ($t_1 = 0.200$ in.) and the adhesive layer ($t_2 = 0.020$ in.) results in:

$$\tau_{max}/\tau_{mean} = (P/2)^{1/2} \coth (P/2)^{1/2}$$

where

$$P = Gl^2/Et_1t_2 = (3.6 \times 10^5 \text{ psi})(1.5 \text{ in.})^2/(10.5 \times 106 \text{ psi})(0.250 \text{ in.})(0.020 \text{ in.})$$

$$P = 12.343$$

So,

$$\tau_{max}/\tau_{mean} = (12.343)^{-1/2} \coth (12.343)^{-1/2} = 1.053$$

This is not a very high degree of stress concentration, so the risk of peel for this combination of adhesive and adherend is not high for this joint.

Given the form of the equation for τ_{max}/τ_{mean}, as P becomes larger, the degree of stress concentration approaches 1.0 (i.e., there is no stress concentration at the ends of the overlap). This occurs as (1) the adhesive gets stiffer relative to the adherend; (2) the modulus of the adherend gets lower relative to the adhesive; (3) the extent of the overlap increases; and (4) either the adherend or adhesive or both get thinner. Contrarily, as P becomes small, the degree of stress concentration increases dramatically, as (1) the adhesive becomes less stiff than the adherends; (2) the adherend becomes very stiff compared to the adhesive; (3) the extent of overlap decreases; and (4) the thickness of the adhesive or adherend or both increases. The relationship between P and τ_{max}/τ_{mean} is shown in Figure 4.14.

Volkerson's shear lag analysis fails to take into account two important factors. First, the two opposing forces applied to the single lap joint are not co-linear, so there will be some bending applied to the joint in addition to the in-plane tension. Second, the adherends are not completely rigid; they bend, allowing the joint to rotate in an attempt to bring the load lines into co-linearity. This rotation actually further alters the

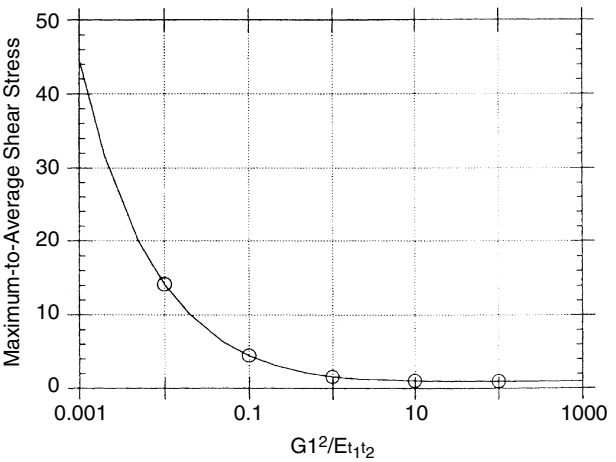


Figure 4.14 Plot showing the relationship between τ_{max}/τ_{mean} and P (= $G1^2/Et_1t_2$) (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 4.12, page 134, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

direction of the load line in the region of the overlap. These factors were taken into account by Goland and Reissner (1944) in their analysis. This analysis will also not be covered here because of its complexity. The analysis treats the single lap joint as a beam undergoing elastic deflection, with one deflection response from the end of the joint element to the start of the overlap and another deflection response in the area of the overlap. At the point where these two meet (i.e., at the ends of the overlap), the two deflections must be the same. Suffice it to say that Goland and Reissner used a factor, k, to relate the bending moment on the adherend at the end of the overlap, M_o, to the applied in-plane loading, F, by the relationship:

$$M_o = kF(t/2) \tag{4.6}$$

where t is the thickness of the adherend (assumed to be the same for both adherends).

If the load on the joint is very small, no rotation of the overlap region occurs and the load acts along the line shown in Figure 4.15a. It can be seen to pass close to the edge of the adherends at the ends of the overlap, so that $M_o = Ft/2$ and $k = 1.0$. In doing so, the line along which the applied load acts moves closer to the centerline or neutral axis of the adherends, as shown in Figure 4.15b. This reduces the value of the bending moment.

Once again, as it was in Volkerson's analysis, the critical result is that an applied load leads to severe out-of-plane stresses at the ends of overlaps for a single lap joint, and these lead to the joint's failure in peel. (The reason will become obvious in Chapter 5, when the peel strength of all adhesives is seen to be an order of magnitude lower than their shear strength!)

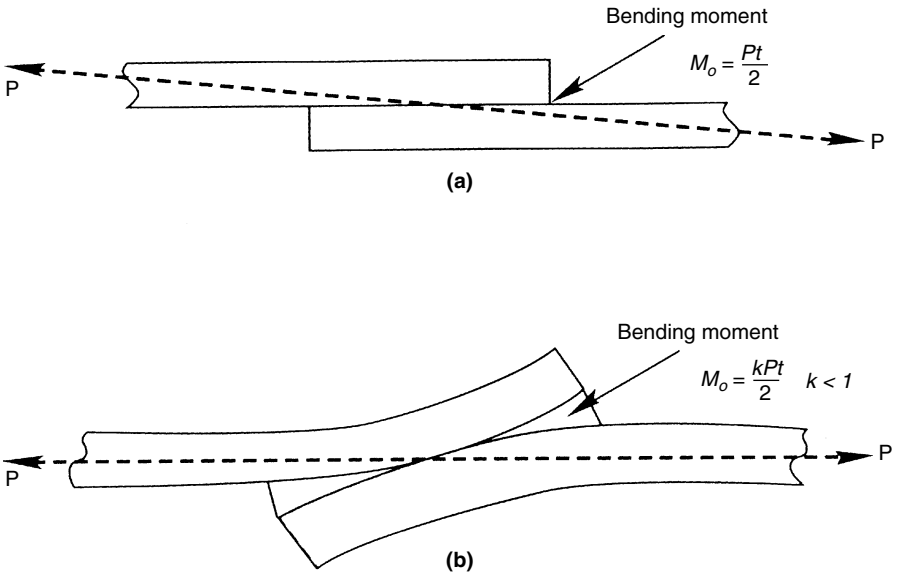


Figure 4.15 Schematic illustration of the bending moment factor of Goland and Reissner, before (a) and after (b) the rotation that occurs in non-rigid bonded joints [1944]. (Reprinted from "Theoretical Stress Analysis of Adhesively Bonded Joints", R.D. Adams, Fig. 2, page 191. In *Joining Technologies for the 1990's*, J.D. Buckley and B.A. Stein, Eds., Noyes Data Corporation, Park Ridge, NJ, 1986, with permission of William Andrew Publishing, Norwich, NY.)

While the analysis of Goland and Reissner includes some simplifications and assumptions, it remains one of the most rigorous mathematical studies of lap joints ever conducted. More recent analyses have been performed for more complex joint designs (e.g., double flat lap, tubular lap, and landed joints) by Pantema, Cornell, Lubkin, Lubkin and Reissner, Mylonas, deBruyne, and McClaren and MacInnes (Patrick, 1967, 1969, 1973). Modern computers have also enabled intricate numerical solutions using finite element methods. Readers interested in the analyses of these more complex joints using numerical methods are referred to specialized sources (e.g., Adams (1984), Adams (1987), Anderson *et al.* (1977), Elliott (1973), and Perry (1958)).

4.6.5 Joint Design Criteria

Before leaving the subject of joint design for adhesive bonding, some general comments related to design criteria are worthwhile.

The previous subsection on joint analysis showed that the stress in the adhesive of a bonded joint is ordinarily a combination of various stresses (e.g., shear, bending, and tension). Furthermore, the relative flexibility of most adhesives to that of most adherends has a pronounced effect on the resulting stress distribution in the joint, often leading to severe stress concentrations with a strong out-of-plane (i.e., peel or cleavage)

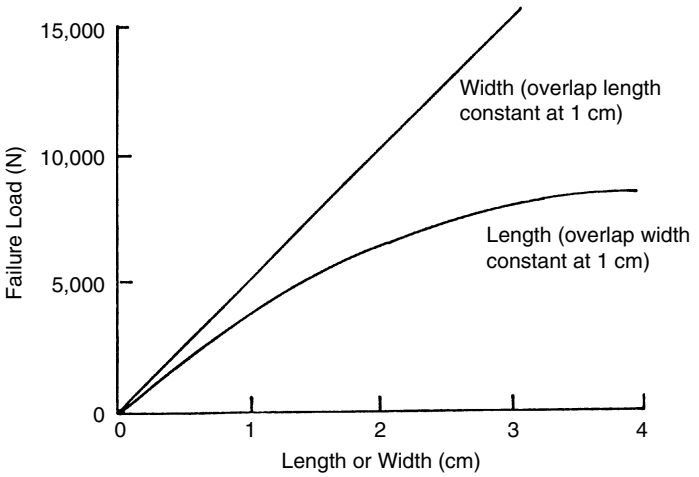


Figure 4.16 Plot of the effect of overlap length and width on the strength of a typical adhesively bonded joint. (Reprinted from *Adhesives Technology Handbook*, A.H. Landrock, Fig. 3.5, page 36, Noyes Publications, 1985, with permission of William Andrew Publishing, Norwich, NY.)

component. Figure 4.16 shows a typical example of a simple single lap joint undergoing tensile loading. It is quickly apparent that most of the stress is concentrated at the ends of the overlap, with most of the rest of the lap carrying a comparatively low stress. As a consequence of this distribution of stress, increasing the overlap length does little to increase the load-carrying capacity of the joint. Far more load-carrying capacity could be gained by increasing the width of the joint. This is shown in Figure 4.16. It can also be seen that for a short overlap length, as in Figure 4.17a, most of the joint is operating above the yield strength of the adhesive. For intermediate (Figure 4.17b) and long (Figure 4.17c) overlap lengths, a portion or most of the joint, respectively, operates at a stress below the yield strength of the adhesive.

A second design criterion is that the bonded area in a joint should be large enough to resist the greatest force that the joint will experience in service, given the allowable stress of the adhesive. Calculation of stress alone is not enough, however, as the effects of environmental conditions, age of the adhesive, temperature of any curing, composition and size of the adherends, and thickness of the adhesive layer must also be considered. As a final criterion, the strength of a lap joint is directly dependent on the yield strength of the adherend, more so as the strength of the adherend is lower.

4.6.6 Methods for Improving Bonded-Joint Efficiency

There are several ways of improving the effectiveness of an adhesive-bonded joint by dealing with the problems of most adhesives' limited strength and flexibility, as these lead to distortion of the joint under non-linear loading. First, the bonded area should be as large as possible, within allowable geometric and weight constraints. This helps keep

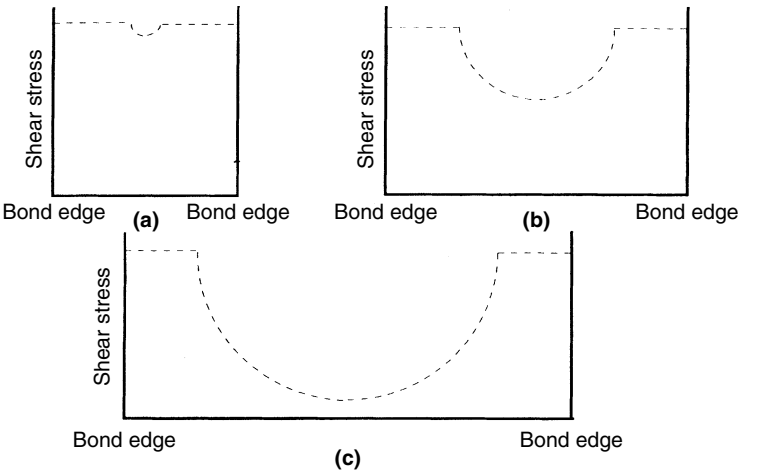


Figure 4.17 Schematic plot of the stress distribution expected for various single flat lap joint overlap lengths, including (a) short overlap, where the stress can exceed the yield strength of the adhesive everywhere; (b) intermediate overlap, where there is some region near the mid-point of the overlap where the stress falls below with adhesive's yield point; and (c) long overlaps, where most of the joint operates below the adhesive's yield point. (Reprinted from *Adhesion and Adhesives*, A.V. Pocius, Fig. 11.5, page 272, Hanser Publishers, Munich, Germany, 1997, with permission.)

the stress in the adhesive low. Second, the maximum possible percentage of the bonded area should contribute to the strength of the joint through (1) proper wetting and (2) keeping the proportion of the joint operating below the yield strength of the adhesive as large as possible (from Hart-Smith (1973)). Third, the adhesive should be stressed in the direction of its maximum strength, which is virtually always in shear. Fourth, stress should be minimized in the direction in which the adhesive is weakest, which is virtually always in out-of-plane peel or cleavage.

It should be obvious that peeling should be avoided wherever and however possible. Peeling can be a particular problem when thin joint members are bonded to thicker members, in which case the operating loads tend to peel the thin member away from the thicker member. Some techniques for improving a joint's resistance to peeling loads include (1) riveting or spot welding (see "rivet-bonding" or "weld-bonding" in Chapter 10); (2) beading the end of the thin member of the joint to provide increased stiffness from moment of inertia; (3) increasing the width of the thin member at the ends of the overlap; or (4) increasing the stiffness of the adherend. These techniques are illustrated schematically in Figure 4.18. The stiffness of joints composed of thin adherends can be increased by using doublers above or below the primary adherend, strong-back stiffeners (e.g., Ts, Ls, inverted Ys, Zs, etc.), formed beads, or other techniques.

In short, adhesive-bonded joints function extremely well under pure compressive or pure tensile loads or under shear produced by co-linear loading. As soon as shear is not co-linear, or tension is not pure, bending occurs, giving rise to a stress distribution

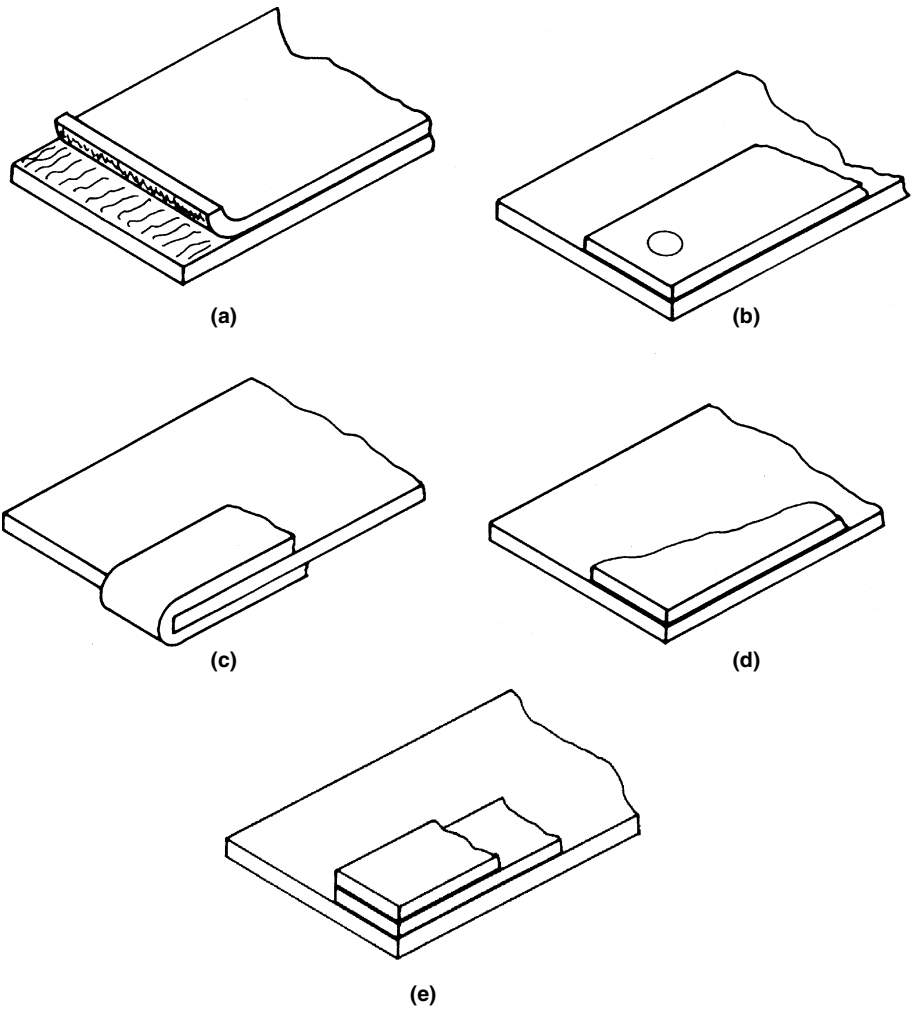


Figure 4.18 Schematic illustration of various methods for enhancing resistance to peel in adhesive-bonded joints (especially with thin-to-thick adherends). (Reprinted from *Adhesives Technology Handbook*, A.H. Landrock, Fig. 3.8, page 39, Noyes Publications, Park Ridge, NJ, 1985, with permission of William Andrew Publishing, Norwich, NY.)

that produces the highest stresses at the edges of overlaps. This, in turn, tends to cause peel or cleavage. Out-of-plane loads can also lead to peel or cleavage, which is always undesirable.

4.7 CEMENT AND MORTAR JOINING AND JOINTS

Without question, the most important adhesive of all—economically and technologically—is mortar. *Mortar* is an all-encompassing term for the bonding material (usually

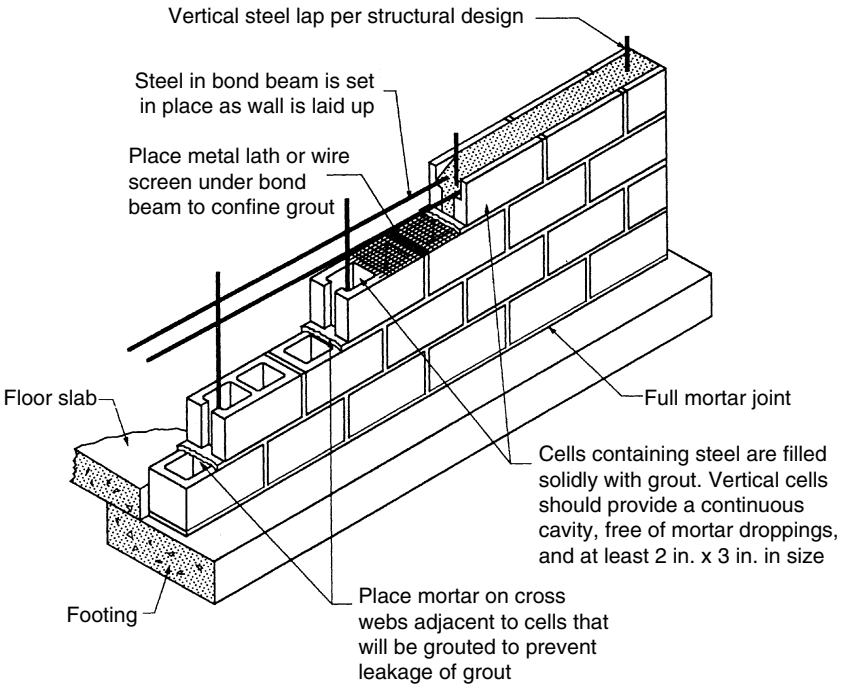
a multi-component material system) used to join masonry units (e.g., stone, clay units or bricks, and concrete units) into structures. Since approximately half of all the material used in the world each year falls into the category of "masonry materials," it is easy to see why mortars are so important.

Chemically, mortars are mixtures of inorganic materials known as ceramics, which are, in turn, compounds of metals and non-metals. In modern usage, the most popular mortar is Portland cement. As will become clear in Chapter 5, when the compositions of mortars and cements are described, these materials form bonds within themselves (i.e., cohesively) as well as with other similar ceramic or "cementitious" materials (i.e., cohesively or adhesively, depending on the closeness of the composition of the masonry units, as the adherends, and the cement or mortar, as the adhesive). These bonds are formed through secondary bonding relying on hydrogen bonds. The process is called "hydration," and the mortars and cements that rely on this process are said to be "hydraulic." What happens is that the ceramic components comprising the cement or mortar bond to water molecules by forming hydrogen bonds with the water. The water molecule, as "water of hydration," literally bonds one ceramic particle to another, forming a bonded aggregate. The resulting strength is quite impressive, as the hydrogen bond is the strongest of the secondary chemical bonds. Full hydration takes time to occur, so cements and mortars require time to cure. It might take only hours or a day to become "set" to appear hard, but it often can take as long as 20 or more days to develop full strength.

The joints used in masonry attempt to do two things. First (and most important), they try to maximize the amount of surface area or interface between the masonry units and the mortar or cement. This is because (as for all adhesive bonding) bonding forces are developed at surfaces or interfaces between the adhesive (i.e., mortar or cement) and the adherends (i.e., masonry units). Second, the resulting joints are made "tortuous," running in many different—and preferably orthogonal—directions. The reason for this is to keep some significant portion of all joints loaded in shear as opposed to out-of-plane tension, because ceramics prefer compression, tolerate shear, and generally abhor tension (see Chapter 12). The combination of long and multi-directional joint paths helps absorb energy trying to tear a joined structure apart and keep as many joints out of a "crack opening mode" as possible.

Figures 4.19 and 4.20 show several anchoring methods and anchors used in cement or concrete construction, especially for joining other materials (not just more cement or concrete) together. Figure 4.21 schematically illustrates various common "laid dry" and "bedded" methods used in stone masonry, with the "sawn" patterns offering the more tortuous path to resist the propagation of cracks both by forcing a longer crack path and forcing the crack in and out of an opening mode.

In modern masonry, cement and concrete blocks, as well as clay bricks, are used to create structures using mortars or cement. The shapes of the blocks and bricks themselves are often designed to do two things to add to joint strength. First, they have combinations of protruding shapes and recesses that cause mechanical interlocking. Second, they have shapes that include hollow sections that allow the mortar or cement to flow through and link the blocks or bricks once it has cured. Other joints used in


Vertical steel lap per structural design
Steel in bond beam is set in place as wall is laid up
Place metal lath or wire screen under bond beam to confine grout
Floor slab
Full mortar joint
Cells containing steel are filled solidly with grout. Vertical cells should provide a continuous cavity, free of mortar droppings, and at least 2 in. x 3 in. in size
Footing
Place mortar on cross webs adjacent to cells that will be grouted to prevent leakage of grout

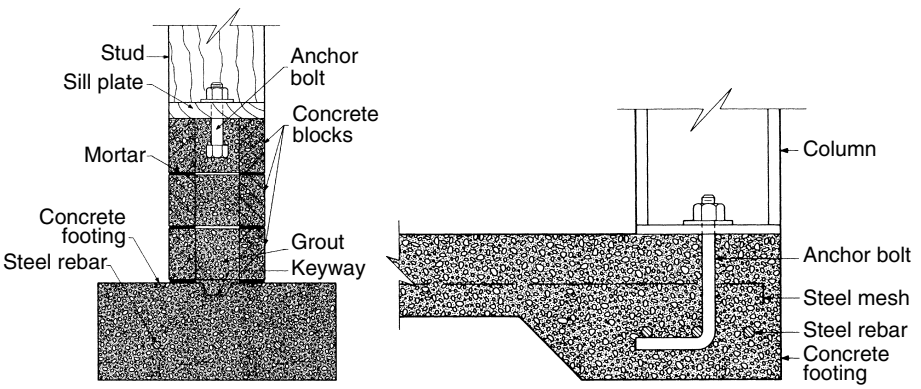


Figure 4.19 Some typical anchoring methods and anchors used to join cement/concrete, steel, or wood structure to cement or concrete structure. (Reprinted from *Masonry Structures: Behavior & Design*, R.G. Drysdale, A.A. Hamid, and L.R. Baker, Prentice Hall, Upper Saddle River, NJ, 1994, with permission of Pearson Education, Upper Saddle River, NJ.)

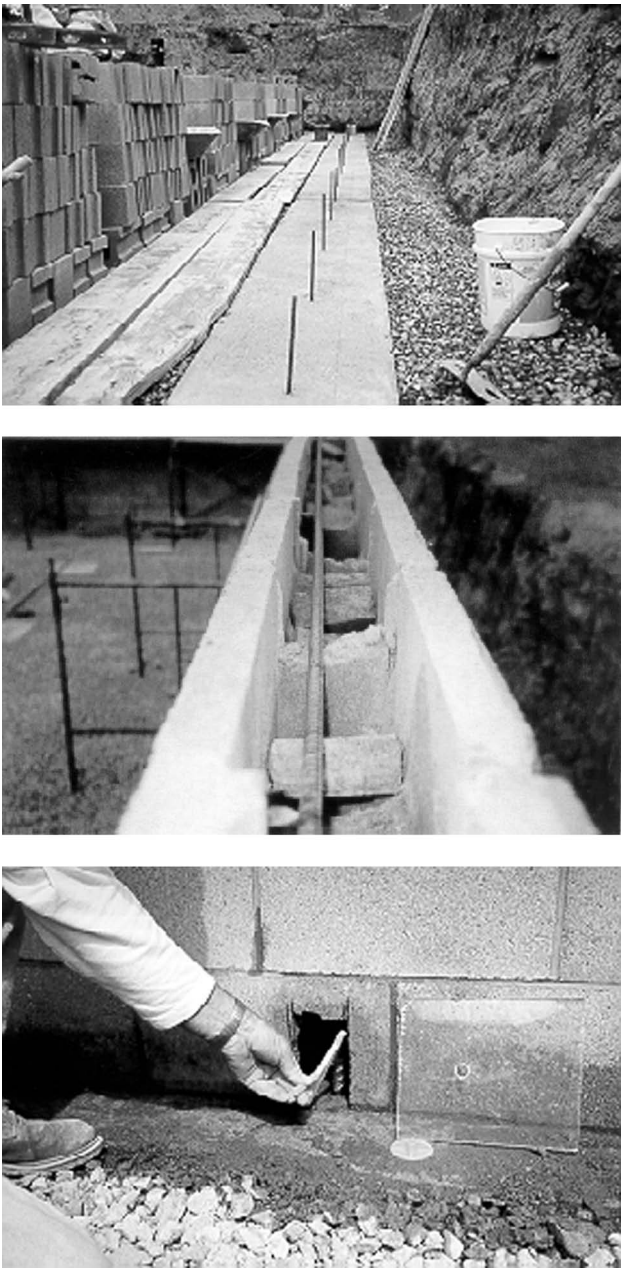


Figure 4.20 Some typical anchoring methods and anchors used in cement and concrete construction, including (a) cast-in-place steel reinforcing rods for strengthening vertical walls, and embedded steel reinforcing rods along walls (b) and around corners of walls (c) to provide additional strength. (Courtesy of the International Masonry Institute, Albany, NY, with permission.)

cement and concrete construction, even in so-called "poured structures," use similar techniques to obtain some mechanical interlocking beyond secondary bonding through hydration (see Chapter 3, Subsection 3.5.3 and Figure 3.41). Examples of some typical joints used in concrete construction are also shown in Figure 4.20.

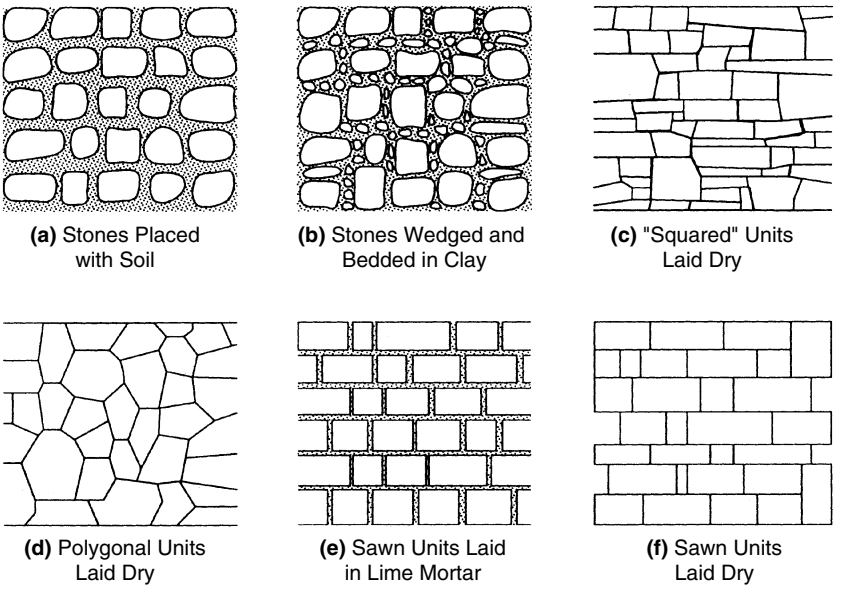

(a) Stones Placed with Soil
(b) Stones Wedged and Bedded in Clay
(c) "Squared" Units Laid Dry
(d) Polygonal Units Laid Dry
(e) Sawn Units Laid in Lime Mortar
(f) Sawn Units Laid Dry

Figure 4.21 Schematic illustration of various common "laid dry" or "bedded" methods used in stone masonry. (Reprinted from *Masonry Structures: Behavior & Design*, R.G. Drysdale, A.A. Hamid, and L.R. Baker, Fig. 1.1, page 3, Prentice Hall, Upper Saddle River, NJ, 1994, with permission of Pearson Education, Upper Saddle River, NJ.)

SUMMARY

Materials can be joined together by creating secondary or, occasionally, primary chemical bonds across an interface using an intermediate substance to facilitate that bonding. This process is called *adhesive bonding.* The intermediate bonding substance is called an *adhesive,* and the materials or structural elements being joined are called *adherends.* The resulting joints can be structural (i.e., intended to transmit stress near the yield limit of one or both of the adherends without losing integrity) or nonstructural (i.e., for the purpose of sealing against fluid leakage or intrusion, to provide electrical or thermal insulation, or to provide mechanical damping). Since the adhesive creates bonding over a large surface area of the joint in a thin layer, stresses from applied loads are distributed uniformly, resulting in improved fatigue life and allowing thin or fragile elements to be joined. Since the adhesive can be made flexible (at least for organic, generally polymeric types), different coefficients of thermal expansion can be accommodated. The process is also ideal for joining dissimilar materials because the

adhesive causes no change in the microstructure and little or no change in the chemical nature of the adherends. Despite these obvious advantages, adhesive bonding has shortcomings, the greatest being the difficulty of inspecting them, the virtual impossibility of repairing bonded joints, and the susceptibility of the adhesive to environmental degradation in service.

Bond strength is attributed to one or more of several mechanisms, including (1) surface adsorption due to wetting of the adherends by the adhesive; (2) electrostatic attraction between oppositely charged layers in the adhesive and adherend brought about by electron exchange due to differences in electronegativity; (3) interdiffusion across the adhesive-adherend interfaces; and (4) some degree of mechanical interlocking between microscopic surface asperities on the adherends through the "wetting" adhesive. Weak boundary layers can form, mostly from contamination left on the adherends, which force premature *adhesive* versus always-preferred *cohesive fracture.* Van der Waal's fluctuating dipole and/or permanent dipole secondary dipole (e.g., hydrogen) bonds are involved in many of these mechanisms. Whatever the mechanism, obtaining a good bond demands thorough cleaning, proper wetting, a proper choice of adhesive, and proper joint design. Joints are judged to be good if they fail cohesively in the adhesive or in one of the adherends, rather than adhesively immediately adjacent to the adhesive–adherend interface in a weak layer. The stresses in joints can be compressive or tensile, giving rise to shear, peel, or cleavage under certain conditions (particularly bending). An adhesive tends to perform best in shear, as this maximizes the load-carrying area, and worst in peel or cleavage, as these tend to load the adhesive non-uniformly in an opening mode through a thin layer. Joint designs attempt to force as much of the applied loading to act in shear as possible, and avoid peeling by incorporating special design features or stiffeners or supplemental mechanical fasteners.

The analysis of adhesive-bonded joints is complex, due to the imperfect shear and the deflection or distortion of most adherends, which leads to non-linear strains and bending moments. Volkerson's shear-lag analysis and Goland and Reissner's improvement accounting for a bending moment factor, give reasonable solutions of shear stress distribution in single lap shear joints.

Mortar and cement joining and joints represent the largest proportion of all adhesive bonding, by far, and rely on the same basic mechanisms for development of bond/joint strength and maximizing joint performance.

QUESTIONS AND PROBLEMS

1. Differentiate between *structural adhesives* and *non-structural adhesives* in terms of the primary role of the adhesive, the level of loading in the adhesive, the level of loading in the adherends, and the criticality of load-bearing to the joint.
2. What are several important functions of adhesives besides holding materials or parts together? Give a typical application where each such function is primary versus load-carrying.

3. What are some of the particular advantages of adhesive bonding as a joining process? What are two specific advantages over mechanical fastening? What are two striking similarities to mechanical fastening?
4. What are some specific limitations of adhesive bonding compared to each of the following?
   - Mechanical fasteners
   - Welding
   - Soldering
5. Several theories have been put forward to explain how adhesives operate by joining one adherend to another, including electrostatic, diffusion, adsorption, and even mechanical mechanisms. The relative contribution of one mechanism over another depends, among other things, on the adhesive–adherend combination. For what types of adherends (by material class) are each of the following particularly important, and for which types are they relatively unimportant or useless?
   - Electrostatic
   - Diffusion
   - Mechanical
6. Explain the role of permanent or induced dipoles in the electrostatic theory of adhesion. What is the role of these bonds in the adsorption theory? What is (are) the difference(s)?
7. Suppose an adhesive joint between a metal and a rubber fails. There is a substantial amount of rubber left on the metal after failure. By what fundamental mode did this failure occur? Is this considered to have been a good joint or not (in terms of the adhesive being a good choice for the adherends)? Would changing to an adhesive with a higher inherent strength help or not?
8. What are the four key steps involved in maximizing the likelihood of producing a good adhesive bond? Give some details associated with each step.
9. What are the five types of simple stress that can occur in adhesively bonded joints? Rank these types from most to least desirable. Give an example of an application or situation where each type predominates.
10. For the scarf joint shown below, what is the shear stress and what is the normal stress in the adhesive? What happens to each of these stresses if the scarf angle is reduced to 15 degrees? Would it be more advantageous to orient the joint at the same scarf angle but with the opposite orientation? Why or why not?

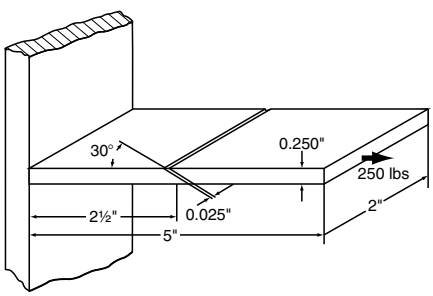


Figure P4.10

11. Suppose the joint shown in Problem #10 was a butt joint. What would be the shear and normal stresses?
12. Suppose the joint shown in Problem #10 had a scarf angle of 30 degrees and adherend thicknesses of 0.250 in. If a force of 100 lbf. were applied vertically downward at the unfixed end (rather than in the plane of the adherends), what would be the shear and normal stresses? How do these compare to the values of shear and normal stress obtained in problem #10?
13. What would the shear and normal stresses be if the scarf angle was decreased to 15 degrees? What if it was increased to 90 degrees? How would the results compare to Problem #10 and #11?
14. For the single flat lap joint shown in Illustrative Example 4.1 in the text, calculate the ratio of the maximum to median shear stress if the adhesive was changed to a flexible silicone adhesive with G = 704 psi (0.48 MPa). All other materials and dimensions remain the same as in the example. How does this ratio compare to the ratio in Illustrative Example 4.1, where a stiffer or more rigid adhesive was used?
15. Calculate the maximum to median shear stress ratio if the adherends in Problem #14 were changed to a nylon 6,6 (i.e., polyamide) thermoplastic, with E = 145,400 psi (993 MPa). How does this compare to the ratio in Problem #14 for a stiffer adherend?
16. Assuming aluminum adherends and an epoxy-type adhesive, as in Illustrative Example 4.1 in the text, what would the ratio of maximum to median shear stress be if the adhesive thickness were reduced to 0.010 in.? What would the ratio be if the adhesive thickness were increased to 0.040 in.? How do these shear stress ratios compare to the ratio obtained in Illustrative Example 4.1?
17. Assuming aluminum adherends and an epoxy-type adhesive, as in Illustrative Example 4.1 in the text, what would the ratio of maximum to median shear stress be if the thickness of the aluminum was decreased to 0.080 in. for the same adhesive thickness (i.e., 0.025 in.)? What would the ratio be if the thickness of the aluminum was increased to 0.500 in. for the same thickness of adhesive (i.e., 0.025 in.)? How do these ratios compare to the ratio obtained in Illustrative Example 4.1?
18. Suppose the adherend in Illustrative Example 4.1 were a thermosetting epoxy with a shear modulus G = 360,000 psi (2,464 MPa or 2.464 GPa), but everything else was the same as in the example, what would be the ratio of maximum to median shear stress? How does this compare to the ratio obtained in Illustrative Example 4.1?
19. Why is it that increasing the length of overlap in a lap joint offers little benefit after a certain point? Approximately how much overlap is considered optimal?
20. What is it about a so-called ''Christmas-tree joint'', which consists of several steps of thickness to produce many lands, that aids greatly in adhesive bonding laminated, unidirectionally, continuously reinforced composites, such as those used in aircraft structures?
21. What changes in the design of a simple, single flat lap joint would minimize peel loading near the ends of the overlap? Explain how each technique works.

22. Explain why brick walls are constructed by staggering alternating rows of bricks so that vertical mortared joints are not aligned. Give at least two ways this technique contributes to the structural integrity of the wall.
23. Explain why bricks and cement (or concrete) blocks often have some form of protrusion on one surface and a matching recess on the opposing surface. How do such features improve the strength of a mortared or cemented joint based on the theories put forward for adhesion?
24. What would you suspect might have to be done when a cemented bricks are used to face a poured cement or concrete wall? (Hint: What would keep the brick facing from separating from the pre-constructed cement or concrete wall?)
25. When Aleut or Inuit people build ice shelters called "igloos" from cut blocks of snow or ice, how do they join these blocks and what is it that makes the joints strong? Which of the mechanisms for causing adhesion are these people using?

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Chapter 5

Adhesives, Cements, Mortars, and the Bonding Process

5.1 INTRODUCTION TO ADHESIVES, CEMENTS, MORTARS, AND THE BONDING PROCESS

Adhesives are substances that are capable of holding materials, and the parts they comprise, together by surface attachment forces arising from the formation of secondary (and, very occasionally, primary) chemical bonds. Sometimes this chemical force-based bonding between adhesive and adherend is augmented by a contribution from mechanical force-based interlocking of the adhesive into asperities on the surfaces of the parts or adherends being joined. Other terms used interchangeably with "adhesive" are "glue," "paste," "mucilage," or "cement." The term "cement" is sometimes applied to certain organic, polymer-based adhesives used especially for rubber (i.e., "rubber cements") and for engineered ceramics (e.g., the well-known "Duco Cement" used to repair china porcelain, among other materials). But it is most commonly associated with a broader and much more widely used subclass of inorganic adhesives known as "mortars," including a major subgroup called "cement," as used to make concrete. Mortars and cements are used extensively and exclusively to join masonry, which includes stone, clay products (like bricks), and cement and concrete products (like cast blocks, precast shapes or units, or poured structures).

Adhesives are used to accomplish adhesive bonding (see Chapter 4), and have applicability to a wide range of materials, in both similar and dissimilar combinations including paper, wood, natural and synthetic fabrics (e.g., cotton and polyester, respectively), leather, polymers (or "plastics"), porous and engineered ceramics (e.g., stone, brick, and cement, and alumina, magnesia, and zirconia, respectively), glasses, metals, and composites of all sorts. They are also being increasingly used with living tissue (e.g., skin and bone). Some adhesives are produced from natural substances or actually occur as "natural adhesives," but most are synthesized chemically as "synthetic adhesives." Adhesives are available in many different chemical types (e.g., phenols, urethanes, epoxies) and can be applied in any of several ways (e.g., spraying, brushing, or pressing as tapes or mastics) in any of several different physical forms (e.g., liquids, pastes, tapes) for a variety of service conditions. As a result, adhesives can be and are classified by any of several different schemes. The resulting properties of

joints can be impressive, whether for structural or nonstructural applications. Degradation from a host of environmental factors can be severe, however, so these factors must be carefully considered in the design of the joint and in the selection and application of the adhesive for the particular adherends, loads, and environment.

This chapter takes a look at adhesives used for accomplishing structural bonding as well as for nonstructural purposes such as sealing, vibration or impact damping, and thermal or electrical insulation. First, the general constituents of adhesives found in what are usually "systems" rather than simply active bonding agents are presented. Then various schemes for classifying adhesives by function, chemical composition, physical form, mode of application, curing or setting, specific adherends, and ultimate use are presented. Some important types or compositions of adhesives are then briefly described, with special attention given to the technologically and economically important subgroup of cements and mortars. Details of the actual process of adhesive bonding are then presented, from adhesive storage through joint adherend and adhesive preparation, to actual joint assembly and curing. The performance of adhesive bonds is then discussed in terms of expected properties, property testing, and joint quality assurance, with special attention given to the effects of the service environment. Again, the properties of important cements and mortars are presented. Finally, major areas of application for various types of adhesives, including cements and mortars, are presented.

5.2 THE CONSTITUENTS OF ADHESIVES

While the common belief is that adhesives are simply "a chemical that causes bonding," the truth is that most adhesives in use today are actually thoughtfully and carefully formulated mixtures of several constituents or components intended to fulfill different functions in producing adhesive-bonded joints (i.e., most are really "adhesive systems"). Basically, an *adhesive system* can contain various combinations of any or all of the following: (1) the adhesive base or binder; (2) a hardener (for thermosetting polymer types); (3) accelerants, inhibitors, or retardants; (4) diluents; (5) solvents or thinners; (6) fillers (for imparting special characteristics or properties); and (7) carriers or reinforcements.

The *adhesive base* or *binder* is the key component of the system, and it is generally the constituent from which the name of the adhesive is derived. For example, an "epoxy adhesive" has an epoxy resin base, possibly with many other constituents such as hardeners, diluents, fillers, or carriers. The function of the base is to create chemical bonds between itself and adherends to hold those adherends together in a joint. It is the active chemical agent in the adhesive. A *hardener* is a substance added to certain types of adhesive bases that require a chemical reaction to cause the adhesive to cure. An example is with thermosetting polymeric adhesive binders. Here, a hardener is required for the long-chain molecules of this polymer to cross-link, thereby becoming rigid or "set." The hardener acts as a chemical catalyst to the cross-linking reaction. The hardener can be pre-mixed with the base and activated by heat or radiation or some other means, or it can be mixed in during adhesive preparation for use, causing the cross-linking reaction to occur spontaneously. The former are referred to as "one-component" or "no-mix" types, while the latter are referred to as "two-component" or

"mix-in" types. *Accelerants, inhibitors*, and *retardants* are substances that are added to control the rate of curing, particularly of thermosetting polymer-type adhesives. Accelerants hasten curing by acting as an additional catalyst for the cure reaction of the base. Retardants slow the rate of curing, while inhibitors arrest it or limit it to retain some tackiness, perhaps. Accelerants and retardants, and especially inhibitors, tend to not be used with or be effective in thermoplastic polymer-type adhesives.

Diluents are components that are added to an adhesive base to reduce the concentration of the base agent. They are used to help control the rate at which and degree to which bonding occurs. They act very much like similar components of pharmaceuticals, where the active ingredient needs to have its potency diluted or its harshness softened. One of the principal functions of diluents is to increase the bulk of the adhesive system if the active base would be too strong by itself and, thus, too small in volume to properly cover the joint surfaces. As such, diluents normally remain in the adhesive after curing or setting. *Solvents* are closely related to diluents in many respects, in that they, too, dilute the active adhesive agent or base. The difference is that solvents are always liquid components added to thin the consistency of the adhesive system (i.e., to lower the viscosity to make adhesive application easier). (See the discussion on Stefan's equation in Subsection 4.3.5.) They do this by dispersing the adhesive base. For many adhesives, solvents play an important part in the way the adhesive cures or sets and accomplishes bonding. In so-called "evaporative" and "diffusion" types of adhesives, solvents either largely evaporate out or are absorbed away by a porous adherend during curing to allow the adhesive to dry and set. They also often serve to thin or soften the adhesive to facilitate interdiffusion. In cement used in bonding masonry, solvents do both. Most of the time, solvents leave the system after full curing, but sometimes some solvent remains behind (either failing to completely evaporate out or becoming entrapped in voids, especially at the adhesive–adherend interfaces). In either case, enough solvent must leave to allow the viscosity of the adhesive to increase, often substantially, to take advantage of Stefan's "tackiness" factor.

Sometimes it is necessary or desirable to modify (i.e., enhance) the base adhesive's properties by adding "filler." *Fillers* are generally nonadhesive substances themselves, and are added to improve the working characteristics of the adhesive (e.g., viscosity, "body," or working time), reduce the amount of shrinkage upon curing or setting (especially when loss of solvent occurs), increase the cured strength, enhance the durability to some environmental factor, and so on. Sometimes fillers are added to attain or adjust certain functional properties like thermal expansion, electrical or thermal conductivity in either direction, or heat resistance. So-called "conductive adhesives" traditionally contain conductive fillers such as metals or conductive carbon (i.e., graphite) added to adhesive bases such as epoxies, urethanes, silicones, and polysulfones. Fillers can also be added simply to reduce the cost of the adhesive system by adding inactive or, at least, non-detrimental bulk.[1]

[1] The best example of adding filler to increase bulk and lower cost is probably concrete. While no one knows for sure, it is likely that the first addition of stones or "aggregate" to a mix of cement was done to add bulk to what is often an application requiring a large volume of material (e.g., paving a highway, pouring a foundation, or building a dam). This reduced the amount of more costly cement provided to the customer, and unintentionally created a structural composite we now know as "concrete."

Carriers and *reinforcements* are sometimes useful for supporting the adhesive during its initial application. Thin fabric or paper can be used as a *carrier*, often as a backing to a semi-cured thermosetting polymeric adhesive or a permanently tacky thermoplastic, or to provide a single- or double-sided support film of adhesive known as a single- or double-sided "tape." *Reinforcements* are added to literally enhance the strength of the adhesive, especially (but not only) during its initial application. Wire screens, fabric meshes, chopped fibers, and steel bars in cement or concrete are commonly used as reinforcements. The carrier or reinforcement (either one) can also serve as a bond-line spacer, or shim, to help establish the appropriate adhesive thickness during initial application. Since the carrier in this case is left in the joint, it is usually designed or formulated to reinforce the adhesive both before and after curing or setting. At minimum, any such carrier must not degrade the performance of the joint.

Table 5.1 summarizes the common constituents of adhesive systems.

Table 5.1 Common Constituents of Adhesive Systems and Their Roles

Adhesive Base or Binder	The active chemical agent responsible for chemical adhesion with the adherend(s).
Hardener	For thermosetting polymeric adhesives and some inorganic adhesives (notably, Portland cement and concrete), a chemical catalyst added to cause the cross-linking reaction or another curing reaction (hydration), respectively.
Accelerant(s) or Retardant(s) or Inhibitor(s)	Additive(s) to speed up the rate of the curing process in the adhesive. Additive(s) to slow down the rate of the curing process in the adhesive. Additive(s) to arrest or limit the extent of the curing reaction (e.g., to retain some tackiness in certain polymeric adhesives).
Diluent	A usually inert component added to the adhesive base to reduce the concentration and, thereby, the potency of the agent. (This function can be provided by the solvent.)
Solvent	A liquid component added to thin the consistency of the adhesive system to facilitate application by a chosen means (e.g., spraying). (The solvent can serve as a diluent.)
Filler(s)	Generally, non-adhesive substances used to impart special working characteristics or properties to the adhesive system (e.g., metal flakes to impart electrical conductivity).
Carrier	A paper or fabric backing to a permanently tacky thermoplastic or a semi-cured thermoset adhesive to facilitate handling during application. (A carrier can, if it remains with the adhesive in service, serve as a reinforcement.)
Reinforcement(s)	Particles, chopped or continuous fibers, or meshes added to the adhesive (or, for the latter, embedded in the adhesive layer) to add strength to the bonded joint.

5.3 CLASSIFICATION SCHEMES FOR ADHESIVES

5.3.1 The Purpose of Classification

Human beings seem to have a primal need to classify things, based on the cognitive way in which our brains acquire knowledge. This need is greater for more complex groups of items, because for such groups it is more necessary to find a way of distinguishing minor and major differences or similarities. Classification is most useful and meaningful when it shows familial relationships (e.g., parent–daughter, sibling–sibling, or close or more distant cousins).

There are a number of different schemes for classifying adhesives, which constitute a very large and diverse group of materials used in joining. While each scheme has its own advantages and serves its own purposes, no one scheme is particularly better than another. Certainly no one particular scheme is universally recognized or accepted. Classification can be by origin, function, chemical composition, physical form, means of application, curing or setting, specific adherend, primary use, or other means. The Society of Manufacturing Engineers (SME) provides an especially useful, in-depth classification based largely on the chemical nature of the adhesive system. The following subsections look briefly at some of the more commonly used classification schemes.

5.3.2 Natural Versus Synthetic Adhesives

Perhaps the most natural way to classify adhesives is by whether they occur naturally or are synthesized. *Natural adhesives* derive their active constituent (i.e., adhesive base) from a natural source (i.e., animal, plant, or mineral). The active agent is a protein, in the case of the animal-based natural adhesives, and usually also for plant-based natural adhesives. Such adhesives can literally be found in nature and can be used as they are found, such as pine tar or pitch, once widely used to bond and/or seal wood to build boats. Alternatively, they can be based on such a naturally occurring adhesive base agent but be designed or formulated to include other constituents, such as a thinner or solvent or a hardener or accelerant for hardening, a filler (e.g., hemp fiber in pine pitch for sealing or "caulking" the joints between planks in a wooden boat), or even a carrier or reinforcement (e.g., a pitch-covered or impregnated woven mesh to strengthen a joint in a wood boat).

Animal sources of adhesive agents include casein (a white, odorless, and tasteless milk or cheese protein), albumin (the white of an egg), blood, ground bone, skin of fish (of which all the preceding can be made into gelatin), and shellac (derived from "lac," a secretion from certain beetles). For animal-based adhesives that are derived from connective tissue, the active protein is collagen-based. One well known commercial adhesive widely used with wood, paper, cardboard, and cloth is Elmer's Glue, made from milk products by the Borden Company. Plant sources of adhesive agents include starch (used to make the paste most of us used in primary school to "paste" construction paper together), resin (from the sap of trees, especially coniferous trees), natural

rubbers (also from the sap of trees, called "rubber trees"), and asphalt (found with or made from bitumens, or soft coals). A natural mineral source is sodium silicate, known as "water glass." Others are various mineral-based gels or, more properly, sol-gels, as well as certain crushed ceramics, such as calcium carbonate (the main component of limestone) and calcium sulfate (a component of lava), used in cement and gypsum, respectively. Most natural adhesives are water soluble and thus depend on the evaporation, absorption, or, in cements and mortars, hydration of water. Except for inorganic cements and mortars, natural adhesives develop low strengths and therefore might not be thought of as structural. They might, however, be used that way for certain low-strength materials. Natural adhesives are used with paper and paper products, wood and wood products, leather, and natural fabrics for lightly loaded joints, and, for these materials, can be considered structural. Except for the cements and mortars, natural adhesives are of little interest in the context of this book (i.e., joining structures).

Synthetic adhesives are just that—they are chemically synthesized adhesive agents, not just synthesized systems containing natural adhesive agents! By this definition, all are polymeric materials, and subclasses include thermosetting polymers, thermoplastic polymers (including elastomeric types), and combinations or "alloys" of these subclasses. All structural adhesives except cements and mortars (which, while based on naturally occurring materials, are actually carefully formulated and processed!) are synthetic.

Some particularly interesting naturally occurring adhesives are those produced by animals for their own use. The most well known examples are the adhesives produced by mussels and barnacles to help them adhere to objects (e.g., pier pilings, ship hulls, whales, other mollusks). Scientific interest runs high in these adhesives for two reasons: First, to know how they work so they can be prevented from adhering to or be removed from ship hulls, for example, and second, to know how to synthesize them for our own use. For example, chemical engineers at Holland's Delft University of Technology have finally figured out that mussels use a protein named Mefp-1 that needs a certain amount of oxygen and a low acidic environment to work. The bioengineered adhesive these engineers are seeking would allow the bonding of living tissue in humans (for example), since, like the mussel's environment, our bodies are saline (in which many adhesives do not work well, if at all!) and low acidic. The resulting "glue" would biodegrade naturally into harmless decomposition products within eight weeks, just in time to allow full healing to occur.

The classification of adhesives as natural versus synthetic might be most useful for predicting biocompatibility for most of the animal- or plant-based examples.

5.3.3 Organic Versus Inorganic Adhesives

Just as natural adhesives can be either organic or inorganic in nature so, too, can synthetic adhesives. Organic adhesives tend to be based on polymers, and for the purpose of this and most other references on adhesives, they are best thought of that way. Such adhesives, whether occurring naturally or being synthesized industrially,

consist of long-chain molecules based on either carbon (in so-called hydrocarbons) or silicon (in silicone-type adhesives). Inorganic adhesives are those that are based on non-metallic compounds of metals and non-metals, in virtually all cases. Examples are the various silicates (most notably sodium silicate), mortars (like gypsum, $CaSO_4 \cdot 2H_2O$), and cements (made from calcined crushed minerals). As a group, organic adhesives have lower strength potential and are less tolerant of temperature extremes and/or fluctuations and many other environmental factors than inorganic adhesives.

This classification is of little practical use except, perhaps, to predict gross strength level and environmental resistance.

5.3.4 Classification by Function: Structural Versus Nonstructural

One of the most general and useful ways of classifying adhesives is by their intended function, which is either structural or nonstructural. *Structural adhesives* consist of adhesive bases or active agents, with or without carriers or reinforcements that provide high strength and reliable performance. Obviously, their primary functions are to hold materials together in structural elements, hold structural elements together in structural assemblies or structures, and sustain and/or transmit high loads therein.[2] Therefore, these are the types of adhesives that are commonly used in load-bearing structures. It is not unusual for a structural adhesive to be stressed to a high proportion of its failing load for long periods of time without exhibiting failure. *Nonstructural adhesives* are also called "holding adhesives," and they are not intended or required to support substantial loads in service. These adhesives have primary purposes other than load carrying, including sealing, vibration damping, impact absorption, and thermal or electrical insulation.

Table 5.2 lists the major functions of adhesives.

5.3.5 Classification by Chemical Composition

At least synthetic adhesives can, quite logically, be classified by their chemical composition. This is, when all is said and done, the most fundamental and universal of all bases for classification of chemical agents! As stated previously, most synthetic adhesives are polymeric materials and, thus, can be subclassified at their highest level by the nature of the polymer comprising the base or binder. These high-level subclasses are (1) thermosetting polymers or thermosets, (2) thermoplastic polymers or thermoplastics, and (3) elastomeric polymers or elastomers.[3] In addition, combinations of these basic subclasses, called polymer alloys (or, usually more accurately, polymer blends) are possible.

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[2] The loads carried by structural adhesives can approach levels that cause yielding or cohesive fracture in one of the adherends.

[3] Elastomers exhibit high degrees of extensibility or flexibility under loading that is fully recoverable when loading is released. Both thermosetting and thermoplastic polymers can be elastomeric. Hence, "elastomeric polymers" are not really distinct from thermosetting or thermoplastic polymers.

Table 5.2 Primary and Secondary Functions for Structural and Nonstructural Adhesives

Structural Adhesives[*]
- Sustain and/or transmit loads or stresses in an assembly of bonded components
- Tolerate the service environment
- Provide needed service life, even permanency
- For many, impart a degree of damage tolerance to the bonded structure
Nonstructural Adhesives[**]
- Tacking or "holding" components until final joining is accomplished by some other means—virtually never adhesive bonding; usually welding or fastening
- Sealing against fluid intrusion or leakage
- Damping of mechanical vibrations
- Absorption (and tolerance) of impact
- Electrical or thermal insulation
- Wear resistance

[*] Structural adhesives can also be selected or designed to provide needed "secondary" functional properties (e.g., electrical conductivity, wear resistance, etc.).

[**] Nonstructural adhesives also provide some bonding, but are not intended for this purpose for any critical load-bearing application.

Thermosetting polymers (see Chapter 13) are those that cannot be heated and softened once they have cured from their initial state. Curing of thermosets takes place by a chemical reaction that leads to the formation of primary bonds (versus normal secondary bonds) between polymer chains known as "cross links," shown schematically in Figure 5.1a. These reactions may take place at either room or elevated temperature, depending on the type of thermoset. In either case, strong ionic or covalent bonds result. These strong bonds from chain to chain serve to rigidize the aggregate of chains, drastically increasing viscosity to the point that the polymer appears hard.

Thermosetting adhesives are based on thermosetting polymers. While they require a chemical reaction to cure, they are available as so-called "one-part" and "two-part" systems. In one-part systems, the chemical catalyst or hardener necessary to cause the chemical reaction leading to cross-linking is premixed into the adhesive base. There it remains, not causing any reaction, until the reaction is activated or triggered by some external energy such as heat or light (often short-wavelength, high-energy ultraviolet or UV light) or some other type of radiation.[4] When heat is used to activate the reaction, curing takes place at an elevated temperature, as opposed to when activation is caused by radiation (like when the dentist activates a thermosetting resin when applying fillings or appliqués to teeth using intense UV light—so as not to burn the patient's mouth!). Shelf or storage life for so-called "no-mix" types is usually limited but can be extended by storing the adhesive in a cool (possibly

[4] In fact, radiation of various types, such as intense gamma radiation (i.e., x-rays), can lead to unwanted cross-linking in, and degradation of, polymers.

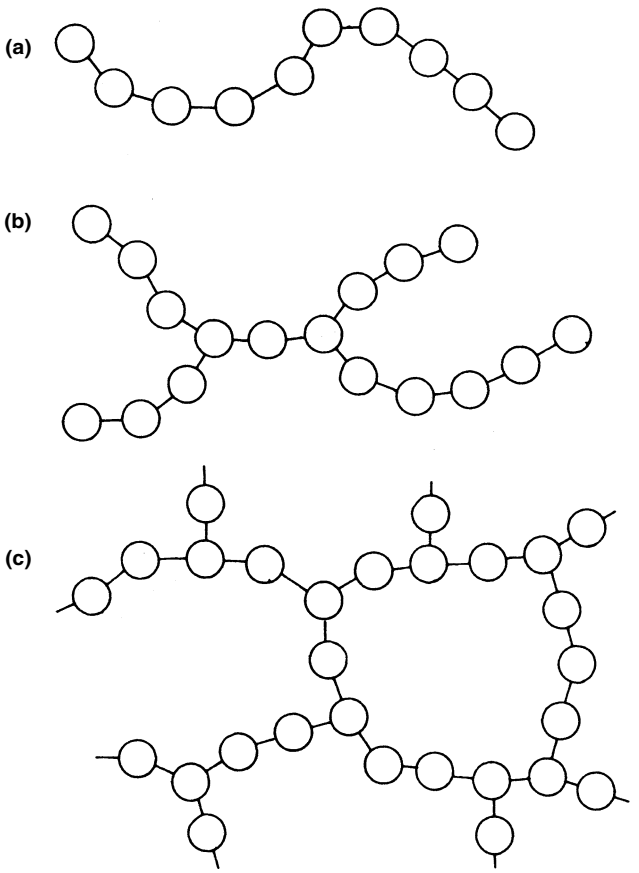

Figure 5.1 Schematic illustrations of the molecular-level structures of (a) a simple linear-chain thermoplastic, (b) a branched thermoplastic, and (c) a cross-linked long-chain thermosetting polymer. (Reprinted from *Adhesion and Adhesives,* A.V. Pocius, Fig. 5.1, page 174, Hanser Publishers, Munich, Germany, 1997.)

refrigerated), usually dark place. In two-part, "mix-in" systems, the hardener or catalyst must be carefully measured and dispensed (i.e., "metered"), added to, and mixed into the adhesive base to initiate the curing reaction without triggering any heat or light, although heat is often used to accelerate the reaction. Once the two components are mixed, working time is limited, although the shelf life of the separate components is usually quite good.

Thermosetting adhesives are usually structural. The dense cross-linking that occurs during curing results in (1) good shear strength from room temperature to about 260°C (500°F); (2) good resistance to heat, with little elastic or creep deformation under loads at moderately elevated temperatures; and (3) good resistance to organic and inorganic solvents. Peel strength is only fair compared to thermoplastic adhesives, however. Most materials can be bonded by thermosetting adhesives, and

major applications are for structural joints that must function at moderately elevated temperatures for long times.

Some important specific thermosetting adhesives include acrylics, anaerobics, cyanoacrylates, epoxies, polybenzimidazole, polyesters, polyimides, polyurethanes, silicones, and urea and melamine formaldehydes.

Thermoplastic adhesives are based on polymers that can be repeatedly softened by heating and stiffened by cooling. The thermoplastic polymers on which these adhesives are based consist of long-chain molecules that do not cross-link between chains to form rigid aggregates during curing (which is really more appropriately called "setting," since they simply "set" or stiffen with cooling). Thermoplastic adhesives are single-component systems that harden either by simply cooling from a melt (e.g., so-called "hot melts") or through the evaporation or absorption of an organic solvent or water used to thin the adhesive initially. Bonding within the thermoplastic polymer involves the formation of only secondary bonds between the long-chain molecules of the polymer and a significant degree of intertwining or tangling of those chains due to entropy (as shown schematically in Figure 5.1b). Most thermoplastic adhesives (except the "hot melts") require solvents as vehicles for carrying the active polymer binder.

As a group, thermoplastic adhesives, like the thermoplastic polymers on which they are based, exhibit limited strength, especially as temperature is increased. Hence, until recently, most thermoplastic adhesives have been nonstructural. More recently developed varieties, and most of the "hot melts," are definitely suited to structural applications, however. Thermoplastic adhesives exhibit the following general properties: (1) service limited to below 65–90°C (150–200°F); (2) poor creep strength; (3) usually poor resistance to organic solvents; and (4) fair peel strength compared to thermosetting adhesives.

Some important varieties of thermoplastic adhesives include acrylics, cellulose acetate, cellulose nitrate, ethylene-vinyl-acetate/polyolefin, phenoxyl, polyvinyl acetate, polyvinyl alcohols, and polyamides (or nylons).

Elastomeric adhesives are based on both natural and synthetic polymers that exhibit superior elongation and toughness. These polymers can be thermosetting or thermoplastic. Because of these properties, elastomeric adhesives are used exclusively for nonstructural applications such as vibration damping, impact absorption, sealing, and accommodating mismatched thermal-expansion coefficients, and for joining elastomeric adherends to one another or to another material.

Elastomeric adhesives are available as solvent solutions, dispersions, or cements (i.e., pastes), and pressure-sensitive tapes. Curing methods vary depending on the specific type and form but include evaporation, absorption, diffusion, and heat. Usually nonstructural, elastomeric adhesives offer high flexibility and superior peel strength, but limited temperature service (up to 70–200°C (150–400°F)) and low bond strength. Elastomeric adhesives offer particular advantages where joint flexure is a key functional attribute or requirement.

Some common varieties of elastomeric adhesives include butyl rubber, natural rubber, neoprene (rubber), polyisobutylene, polysulfide, polyurethane, reclaimed rubber, and silicone.

Adhesive alloys are literally combinations, or alloys,[5] of resins from two or more chemical groups from among thermosetting, thermoplastic, and elastomeric types. When properly formulated, adhesive alloys utilize the most important or desirable properties of each component. A good example is an adhesive alloy containing a thermosetting resin chosen for its high strength, made tougher or "plasticized" through the use of an elastomer chosen for its inherent toughness, flexibility, and resistance to impact. Adhesive alloys are available as solvent solutions, and as supported and unsupported films. Heat and pressure are usually required for curing, except for some epoxy types.

Adhesive alloys are definitely intended to be structural adhesives and should be considered where the highest and most stringent service conditions must be met. Costs can be high but are often justifiable for the needed performance characteristics that can be obtained. As might be expected, adhesive alloys are excellent for joining dissimilar materials to one another, such as metals, ceramics, glasses, and thermosetting and thermoplastic polymers.

Some common varieties of adhesive alloys include epoxy–phenolics (a thermosetting alloy), epoxy–polysulfone (a thermosetting alloy), epoxy–nylon (a thermosetting–thermoplastic alloy), neoprene–phenolic (an elastomeric–thermosetting alloy), and vinyl–phenolic (a thermoplastic–thermosetting alloy).

The Society of Manufacturing Engineers (SME) classifies adhesives into a number of divisions based largely on chemical composition, as described in the following paragraphs. *Chemically reactive adhesives* require something to trigger the curing reaction in a thermosetting base or binder. These adhesives include one-component systems that are cured by moisture from the air or from an adsorbed layer on the adherend, by heat, or by exclusion of oxygen (i.e., anaerobic), and two-component systems where the hardener is premixed (called "no-mix" types) and activated by heat or where the hardener is metered and mixed in to start the curing reaction spontaneously (called "mixed-in" types). The most commonly used chemically reactive structural adhesives include epoxies and modified epoxies, modified acrylics, anaerobics, cyanoacrylates, silicones, polyurethanes, phenolics, and the high-temperature polyimides and polybenzimidazoles.

Evaporative or *diffusion adhesives* are organic solvent-based or water-based systems that rely on the evaporation or adsorption or diffusion of solvent into the air or into a porous adherend, respectively, to cause the adhesive to cure. Popular solvent-based adhesives include acrylics, phenolics, polyurethanes, vinyls, and a variety of natural and synthetic rubbers. Water-based adhesives include those that are totally soluble and those that are dispersive in water. Popular systems include certain acrylics, certain vinyls, and certain natural and synthetic rubbers.

A quite new variety of these adhesives operates by what is referred to as "diffusion-enhanced adhesion," or DEA. It was initially developed for use with either thermoplastic or thermosetting polymers and composites, in similar or dissimilar combinations. Interdiffusion of monomers and thermoplastic polymer chains greatly enhances adhesion.

[5] To be correct, most so-called "adhesive alloys" are really only blends of different polymeric adhesives, although actual molecular-level alloys exist in which the long-chain polymer molecules themselves contain a portion of two or more different fundamental types of polymers (e.g., thermosets and thermoplastics).

Hot-melt adhesives are 100% thermoplastic systems that remain solid to a certain temperature, at which point they seem to melt abruptly (actually, they just soften). Upon melting, these adhesives are applied to the adherends and allowed to set. Specific hot melts are discussed in Subsection 5.4.8.

Delayed-tack adhesives use solid plasticizers in their formulation that are activated and made tacky by heating. The resulting tackiness persists after heat activation and can last from minutes to days over a wide temperature range. Some common solid plasticizers include dicyclohexyl phthalate, diphenyl phthalate, and ortho- and para-toluene sulfonamide. Popular bases for delayed-tack adhesives include styrene–butadiene copolymers, polyvinyl acetates, polystyrenes, and polyamides (nylons).

Pressure-sensitive adhesives are based on rubbers (such as natural rubber, styrene–butadiene rubber, reclaimed rubber, butyl rubber, and nitrile rubber, as well as polyacrylates and polyvinylalkylethers) compounded with tackifiers. The application of pressure to force the adhesive and adherends into intimate contact causes the adhesive and adherend to immediately adhere together. Often, no curing is needed or occurs. Adhesion is strictly the result of the adhesive and adherend being in contact. (As a matter of practicality, most pressure-sensitive adhesives apply a thin or light layer of adhesive to each adherend and then bring the two ''primed'' adherends into intimate contact under pressure.)

Film and tape adhesives use high-molecular-weight backbone polymers as carriers to provide toughness, elongation, and peel strength (i.e., some additional mechanical resistance to out-of-plane loads). A low-molecular-weight cross-linking resin and curing agent or catalyst is used as the adhesive.

Conductive adhesives include both electrically and thermally conductive types based on epoxies, polyurethanes, silicones, and polyimides. Conductive or insulating properties are almost always obtained with the addition of fillers, which themselves have the electrical or thermal properties desired in the adhesive system. For electrical conductivity as well as for thermal conductivity, silver flakes or powder or aluminum and copper fillers are used (up to 85 volume percent), with chemical compatibility with the other constituents of the adhesive (especially the active agent) being the deciding factor. For thermal conductivity, beryllia, boron nitride, and silica are used, while for thermal insulation, alumina is used.

Table 5.3 summarizes the SME chemical composition classification scheme for adhesives.

While by no means comprehensive, Table 5.4 shows which adhesive types work best with which adherends. More complete information on recommendations of specific adhesives for specific adherends is available in various handbooks (ASM International (1990), Cagle (1973), Landrock (1985), Shields (1984), and Skeist (1989)).

In conclusion, for engineers, classification by chemical composition is, ultimately, the only meaningful way to classify adhesives, as only this means of classification can ensure reproducibility when ordering more material from the same or other producers.

Table 5.3 Summary of Major Structural Adhesives Under the SME Classification Scheme

Chemically Reactive					
Chemical Cure	*Moisture Cure*	*Heat-activated Cure*	*No Oxygen Cure*	*Mix-in*	*No-mix*
Epoxies	Silicones	Polybenzimidazoles	Anaerobics	Epoxies	Modified acrylics
Phenolics	Polyurethanes	Polyimides		Polyurethanes	
Polysulfides	Polysulfides	Epoxies		Modified acrylics	
Polyurethanes	Cyanoacrylates	Nylons		Silicones	
Polyesters	Epoxies	Phenolics		Phenolics	
Resorcinol-formaldehyde		Polyvinyl acetates			
		Urethanes			

Evaporation or Diffusion			*Hot Melt*	
Organic-Solvent Base		*Water Base*	*General Purpose*	*High Performance*
Natural rubber	Phenolics	Natural rubber	Ethylene–vinyl acetate copolymers	Polyimides
Reclaimed rubber	Urethanes	Reclaimed rubber	Polyolefins	Polyesters
Synthetic rubbers (nitrile, neoprene, butyl-neoprene-butadienes)	Vinyl resins (polyvinyl acetate, vinyl phenolic, polyvinyl esters, polystyrene)	Synthetic rubbers	Thermoplastic elastomers	
		Vinyl resins		
		Acrylics		
Phenoxy resins		Natural adhesives (animal glues, starch)		
Polysulfones	Acrylics			
	Polyamides			

Delayed Tack	*Film and Tape*	*Pressure-Sensitive Film and Tape*	*Electrically and Thermally Conductive*
Styrene–butadiene copolymers	Nylon-epoxies	Natural rubbers	Epoxies
Polyvinyl acetates	Elastomer-epoxies	Styrene–butadiene rubber	Polyurethanes
Polystyrene	Nitrile-epoxies	Reclaimed rubber	Silicones
Polyamides	Vinyl phenolics	Butyl rubber	Polyimides
	Epoxy phenolics	Polyacrylates	
	Polyimides	Polyvinylalkylethers	
	Polybenzimidazoles		

5.3.6 Classification by Physical Form

As will be seen in Subsection 5.3.7, adhesives can also readily be classified by the way in which they are applied, which is based on their physical form. Thus, the physical form of the adhesive is a useful way of classifying adhesives, especially in the context of manufacturing, construction, or other use (e.g., repair). The forms in which adhesives can be found (and, thus, classified) include (1) liquid adhesives, (2) paste adhesives, (3) dry powder (or powdered) or granular (or granulated) adhesives, and (4) tape and film adhesives.

Table 5.4 Summary of Adhesive Types Versus Compatible Adherends

	Metal																
Adhesive	*Al*	*Ag*	*Au*	*Be*	*Brass/ Bronze*	*Cd*	*Cu*	*Mg*	*Ni*	*Pb*	*Sn*	*Steel*	*Stainless Steel*	*Ti*	*U*	*W*	*Zn*
Acrylics					•		•					•	•				
2nd-generation acrylics	•																
Anaerobics			•		•	•	•										
Cyanoacrylates	•						•	•		•							•
Epoxies		•	•	•	•		•	•	•	•	•	•	•	•	•	•	•
Epoxy–phenolics	•		•	•				•		•		•	•	•			
Modified epoxies	•																
Modified phenolics	•																
Neoprene–phenolics	•				•		•	•									
Nitrile–epoxies	•			•									•	•			
Nitrile–phenolics				•		•	•	•	•			•	•	•			
Nitrile–rubbers																•	
Nylon–epoxy				•	•		•	•	•								
Polyacrylates										•	•						
Polyamides									•								
Polybenzimidazoles				•					•			•	•				
Polymides				•					•			•	•	•			
Polyurethanes				•	•		•	•		•							
Polyvinyl acetates								•									
Polyvinylalkylether		•	•							•	•						•
Silicones	•				•		•	•		•							
Styrene–butadiene											•						
Vinyl–plasticols	•																
Vinyl–phenolics								•	•								

Table 5.4 (*Continued*)

	Polymers																					
	T/Ps															*T/Ss*						
Adhesives	*ABS*	*Celluloses*	*Fluoroplastics*	*Nylons (polyamides)*	*Polycarbonates*	*Polyester*	*PEEK*	*Polyethersulfane*	*Polyethylene*	*Polymethylmethaerylate*	*Polypropylene*	*Polystyrene*	*Polysulfane*	*Polyvinylchloride*		*Epoxies*	*Melamines*	*Phenolics*	*Polyester*	*Polyurethane*	*Silicone resin*	*Ureaformaldehyde*
Acrylics													•									
2nd generation acrylics	•										•											
Anaerobics			•													•	•	•		•		
Butadiene–nitrile																	•					
Cyanoacrylates	•	•		•	•	•	•	•			•		•			•	•	•	•			•
Epoxies	•	•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	•	•		•
Epoxy-phenolics																•	•		•			
Melamine–formaldehyde																•						
Modified acrylic		•														•			•	•		
Modified epoxy				•						•						•			•		•	
Neoprene			•												•				•	•	•	•
Nitrile–phenolic	•	•								•		•				•	•	•	•			•
Phenol–formaldehyde				•												•						•
Phenolic																			•			
Phenolic–polyvinylbutyral																•	•		•			•
Polyacrylates		•																	•			
Polyamide–epoxy													•									
Polyester																•			•	•		•
Polyurethanes	•	•	•	•	•	•							•	•	•	•			•		•	
Resorcinol–formaldehyde		•		•													•				•	•
Rubber–phenolic																			•			
Silicones					•	•				•											•	
Solvent cementing		•		•	•	•			•	•	•		•			•						
Urea–formaldehyde													•				•	•				•
Vinyls	•																					

Reinforced Plastics/Composites
- Solvent cementing
- Adhesive based on matrix

Rigid Plastic Foams
- Solvent cementing
- Water-based adhesives
- Epoxies

Rubbers
- Neoprene
- Nitrile rubber

Glass
- Transparent heat-setting resins (e.g., polyvinyl butyral, phenolic butyral, nitrile–phenolic, neoprene, polysulfide, silicone, vinyl acetate, and epoxies)

Ceramics
- Epoxies
- 2nd generation acrylics
- Polysulfides

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Liquid adhesives offer easy application on adherends of any shape or roughness because of their low viscosity. They can be applied manually or automatically, using brushes, using mechanical spreaders, or as liquid or mist (including aerosol) sprays. Frequently, liquid adhesive systems include solvents in their formulation to "thin" them. Paste adhesives have higher viscosities than liquid adhesives to give the adhesive more "body." Body permits application in controlled thickness and allows application on vertical or steeply sloped or contoured surfaces without running, dripping, or sagging. Paste adhesives are good for filling gaps between poorly fitting mated surfaces. Body is usually achieved through the balanced use of solvents (and, possibly, diluents) and fillers. Tape and film adhesives provide a uniformly thick layer of adhesive, and thus control the bond line very precisely. This can be very important in some loading situations, without the use of elaborate applicators, metering, or shims. They are limited to geometric shapes with less severe curvature and cannot be used to take up gaps. These adhesives are supported on carriers of paper (e.g., masking tape), cloth (e.g., duct tape), or plastic (e.g., Scotch tape or electrical tape), which sometimes can be peeled away to leave just the adhesive, as is the case with film adhesives. Thus, these forms are easily dispensed and handled. Finally, powder or granular adhesives are powdered or granulated dry solid adhesive agents, possibly with added diluents or fillers. Some of these (among the organic polymer versus inorganic types) need to be heated to be made fluid enough to cover the adherend surfaces with a uniformly thick, adhering coating. "Hot melts" are a good example. The best known dry powder adhesives are, by far, masonry cements and mortars.

This classification scheme is most useful for aiding process engineers as well as home "do-it-yourselfers" choosing an appropriate adhesive for a job.

5.3.7 Classification by Mode of Application or by Curing or Setting Mechanism

It is often useful, especially for purposes of planning in manufacturing or construction, OEM[6] or repair, to classify adhesives by the way in which they can or must be applied, and/or activated and cured or set. Depending on viscosity, adhesives can be considered (1) sprayable, (2) brushable, (3) trowelable, (4) or extrudable using metered pumps, caulking guns, or syringes.

Another useful way of classifying adhesives for manufacturing purposes is by the way in which they flow or solidify or are activated and cured or set. Some solidify or harden by losing solvent by evaporation or absorption, others require heat and/or a chemical catalyst to harden by cross-linking (e.g., thermosetting types), others require pressure to flow but become stable when pressure is removed, and still others (e.g., thermoplastic types) simply need to cool and become more viscous. Thus, there are adhesives that require the following: (1) heat to flow or to cure, or both; (2) pressure to flow during application or to actually initiate the adhesion process (in "pressure-sensitive" adhesives); (3) time to cure at room temperature (say, by solvent evaporation

[6] OEM stands for "original equipment manufacturing."

or absorption); (4) a catalyst to cure, with or without heat or UV irradiation and/or pressure; and (5) reactivation to cure with the aid of heat or solvent.

5.3.8 Classification by Specific Adherend or by Application

It is possible, and sometimes useful, to classify adhesives according to their end use, either by the specific adherend to which they are best suited or by intended environment. Examples of adhesives for specific adherends include wood glues, metal adhesives, ceramic cements, rubber cements, and vinyl adhesives. Examples of adhesives intended for specific environments include heat-resistant adhesives, cryogenic adhesives, acid-resistant adhesives, weatherable (or weather-resistant) adhesives, and general-purpose adhesives for non-critical applications.

There are other classification schemes, but the ones presented here are fairly comprehensive, are the most common, and make the key point that classification is important and useful.

5.3.9 Classification of Cements and Mortars

As a verb, to "cement" means to bind two substances together, but as a noun it is much more confusing. It is the name for certain kinds of glues or adhesive materials used in dentistry and for certain organic and many inorganic bonding agents used to join engineered ceramics, including porcelains. It is also the common name of certain organic (polymer-based) adhesives used to bond rubber (i.e., "rubber cements"). But, in the most common usage of all, it is the name of a material used for joining in masonry (i.e., the joining of stone, clay products, or cement or concrete products). In this last context, it is a substance that is a nonmetallic, inorganic compound known as a ceramic that binds particulate aggregates into a cohesive structure through a chemical reaction. With so-called "hydraulic cements," the chemical reaction is one of hydration (see Chapter 12, Subsection 12.3.2), involving hydrogen bonding of ceramic particles with water molecules. (Figure 12.1 schematically classifies ceramic materials on the basis of application and shows where cements fit in this classification scheme.)

There is actually a wide variety of cementitious materials (i.e., materials having the characteristics of cement) used for different purposes, and it is on this basis that cements are best classified. Table 5.5 lists various cements used in a variety of applications and industries. The most well known and widely used class of cement used is referred to as "Portland cement." While details of Portland cement, as well as some other cements, are given in Chapter 12, Subsection 12.3.2, suffice it to say here that Portland cement has an overall composition in which the major resulting constituents are tricalcium silicate ($3CaO \cdot SiO_2$) and dicalcium silicate ($2CaO \cdot SiO_2$). There are also relatively minor additions of tricalcium aluminate ($3CaO \cdot Al_2O_3$), brown-millerite (approximately $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$), some CaO, some MgO, and glass. The amounts, composition, and morphology of the minor phases present depend principally on the raw material used and conditions employed for sintering the cement in its

Table 5.5 Major Types of Cements and Mortars

Masonry Cements and Mortars	
Gypsum cement or mortar	$CaCO_3$ and $CaSO_4$
Portland cements (Grades I-V)	Mixtures of C_3S, C_2S, C_3A, C_4AF and other oxides and $CaSO_4$ (see text and Table 5.6)
Refractory (aluminous) cements	35–42% CaO + 38–48% Al_2O_3 + 3–11% SiO_2 + 2–15% FeO
Concretes	
Air-entrained concrete	5–7.5% volume air based on max. aggregate size
Lightweight structural concrete	Shale, clay, slate, fly ash, blast furnace slag aggregate
Lightweight insulating concrete	As above, plus air
Heavyweight concrete	Added Fe, Ti, or Ba in aggregate
Hot weather concrete	Grade II or IV Portland cement (see Table 5.7)
Cold weather concrete	Added $CaCl_2$ (2% max.) to accelerate curing
Special Cements and Mortars (see Table 5.8)	
Acid-proof cement	
Adhesive cement	
Electrical insulating cement	
Electrical resistance cement	
Electric heater cement	
Electric refractory cement	
Electrotemp cement	
High temperature cement	
Low expansion cement	

manufacture. This notwithstanding, there are also five ASTM-specified types of Portland cements (see Chapter 12, Subsection 12.3.2, Table 12.4) having different characteristics arising from different compositions.

The other really important cement, technologically and economically, is "high-alumina cement," which is used for refractory (i.e., extreme elevated temperature) applications and service. These typically contain approximately 40 parts Al_2O_3, 40 parts CaO, 7 parts SiO_2, 7 parts Fe_2O_3, 5 parts FeO, and five other minor oxides.

The term "mortar," when used properly, refers to a mixture of materials to enable the "bedding" and bonding of masonry units. In its most common form, mortar is referred to as "lime mortar," because it is a combination of Portland cement, lime (CaO), sand (predominantly SiO_2), and water mixed in specific proportions. The most common is designated 1:1:6 Portland cement–lime mortar, having equal parts of Portland cement and lime, with sand volume six times the Portland cement volume or three times the volume of the total cementitious material. Basically, the Portland cement gives strength, the lime contributes to workability, and the sand provides an

inexpensive filler. Table 12.5 (in Chapter 12) lists the proportion specification for various mortars classified as M, S, N, O, and K in North America.[7]

Like virtually all adhesives, cements and mortars are actually complex mixtures of a variety of constituents with different purposes. In cements and mortars, the following are typically found as part of the inorganic adhesive "system": (1) active agent or base (e.g., Portland cement in Portland cement–lime mortar); (2) "admixtures," which act as either plasticizers to toughen the final product or accelerators or retardants to serve as workability agents; (3) dyes to color the final product; (5) filler (usually sand); and (6) other aggregates (such as stones) to add composite strength as well as bulk.

5.4 IMPORTANT ORGANIC STRUCTURAL ADHESIVES

5.4.1 General Description of Organic Structural Adhesives

"Organic adhesives" are those whose active agent or base is itself based on an organic molecule (or, in some cases, such as "adhesive alloys," several organic molecules). In animal- and plant-based natural adhesives, that molecule is a protein: casein in milk-based adhesives, albumen in egg-based adhesives, and collagen in connective tissue–based adhesives. In synthetic organic adhesives, that molecule is either a long (i.e., high molecular-weight) carbon-based chain (e.g., a hydrocarbon) or a silicon-based chain (e.g., in silicone adhesives). "Organic structural adhesives" are those organic adhesives that are capable of carrying loads that are high relative to the cohesive strength of the adherends they are used to bond. Based on this definition, animal- and plant-based natural adhesives will not be described in this section. Synthetic, polymer-based adhesives will be described very briefly, just to give the reader a sense of what the most important types are. Detailed explanations of the underlying chemistry of these major types are covered extremely well in references dedicated to adhesives, such as Pocius (1997).

5.4.2 Epoxies and Modified Epoxies

Epoxy resins[8] are the reaction product of acetone and phenol and are, by far, the most popular and diverse of all structural synthetic organic adhesives used today. *Epoxies*, or more properly, *epoxide adhesives*, are thermosetting polymer resins usually based on diglycidyl ether of bisphenol-A (DGEBA). They cure upon heating or exposure to

[7] These designations simply correspond to every second letter in the words MaSoN wOrK.

[8] The term "resin" has been (and will continue to be) used throughout this book. It has two meanings, one or the other of which applies to a particular discussion. According to Houghton Mifflin's *American Heritage Dictionary*, a "resin" is: (1) "Any of numerous clear to translucent yellow or brown solid or semi-solid (i.e., viscoelastic) viscous substances of plant origin, such as copal, rosin, and amber, used principally in lacquers, varnishes, inks, adhesives, synthetic plastics, and pharmaceuticals," or (2) "Any of numerous physically similar polymerized synthetics or chemically modified natural resins including thermoplastic materials, such as polyvinyl, polystyrene, and polyethylene, and thermosetting materials such as polyesters, epoxies, and silicones, that are used with fillers, stabilizers, pigments, and other components to form plastics."

other radiation (for one-part systems) or through the addition of a hardener or catalyst (in two-part systems) or both, with little or no need for pressure other than to hold adherends in contact. Upon curing, epoxies become rigid through the formation of dense cross-linking (see Figure 5.1a). There are more than 25 different specific types of epoxy resins, and more than 60 known hardeners, including aliphatic polyamines, fatty polyamines, aromatic polyamines, and boron trifluoride monoethylamine. The cross-linking reaction is exothermic (i.e., gives off heat), and this must be taken into account in practice to avoid overheating and the formation of pores during curing. Aside from hardeners (whether they are pre-mixed or mixed in), other additives such as accelerators, reactive diluents, plasticizers, fillers, and resin modifiers are often used to modify behavior or impart special properties.

Epoxy adhesives can be used to join most materials, including metals, ceramics (including cement and concrete), and polymers, all with good results. The highest strengths (up to 77.2 MPa or 10 ksi in shear) and best heat resistance are obtained with heat-cured, two-part types. As a group, shrinkage is low and bond flexibility tends to be low, so impact strength is poor and fatigue resistance is low. Peel strength also tends to be low. Like most thermosetting polymers, resistance to solvents is good.

Because thermosetting adhesives, as a group, exhibit brittle behavior when cured, an important group of adhesive alloys has emerged called "modified epoxies." *Modified epoxies* incorporate various thermoplastics (including elastomeric types) and elastomeric thermosets to impart flexibility and toughness and better resistance to peel. Examples include epoxy-nylon, epoxy-polysulfide, epoxy-phenolic, and epoxy-nitrile (rubber). These modified types of adhesives, made up entirely of solids, contain no solvent. Thus, shrinkage is low and bonding to impervious surfaces on adherends is possible. They also exhibit excellent wetting on metals, glass, and ceramics, and so are excellent for bonding similar and dissimilar combinations of these materials.

5.4.3 Acrylics and Modified Acrylics

The acrylic family of synthetic organic adhesives is based on acrylic monomers of ethyl acrylate, methyl acrylate, methacrylic acid, acrylic acid, acrylamide, and acrylonitrile. They are all two-part systems but are not mixed for application. Rather, the resin is applied to one adherend and the accelerant is applied to the other adherend. When these two are mated, the bonding reaction occurs quickly (in minutes) even at room temperature. Pretreated parts can be stored separately for some time before bonding. Shear strengths can reach 28 MPa (4 ksi).

New formulations of acrylics, called "second-generation" or "reactive acrylic adhesives," have additives that penetrate hydrocarbon contaminants (e.g., oils and greases) on adherends, incorporating that hydrocarbon into the structure of the cured adhesive and enhancing bonding significantly. These second generation acrylics make metal-to-metal structural bonding practical where it may not have been practical before (e.g., in the automobile industry), and are generally referred to as "modified acrylics." *Modified acrylics* also offer good peel strength, impact resistance, and tensile shear lap strength over the temperature range from −110–120°C (−160–250°F). High

temperature strength, on the other hand, is low. As a group, modified acrylics are quite flammable.

Examples of modified acrylics include acrylic–latex, acrylated silicones, acryliated urethanes, and acrylated silicone–urethanes. Silicone[9] additions improve thermal stability, tensile strength, and resistance to solvents, abrasion, and ultraviolet radiation (e.g., sunlight). They also offer improved adhesion to ceramics and metals over traditional acrylics.

5.4.4 Cyanoacrylates

Cyanoacrylates, or "super glues," as they are known by consumers, are composed of low-viscosity liquid acrylic monomers that polymerize easily in the presence of adsorbed water, especially where the adherend surface is slightly alkaline. Polymerization is ionic, and strong thermosetting bonds can be created with many materials, especially metals to nonmetals, with no added heat or catalyst, since most surfaces have adsorbed water present. Not surprisingly, cyanoacrylates are also used to adhesively bond living tissue, as such tissue also contains suitable water to trigger the polymerization reaction.[10]

The shear strengths of cyanoacrylates are good, up to 38.6 MPa (5 ksi), although peel strength and impact resistance are low and tolerance of moisture is poor. The principal advantage of cyanoacrylates is that they bond in seconds—virtually instantaneously. One important use is for holding components in place (for jigging), until some other more permanent joining process (such as spot welding, in the automobile industry) is accomplished. When used this way, they are "holding compounds."

Cyanoacrylates will bond with almost any substrate, hence their more familiar name of "super glues." Methyl cyanoacrylate produces stronger and more impact resistant joints than ethyl cyanoacrylate when bonding metals and other rigid adherends. Ethyl cyanoacrylate, however, produces stronger and more durable joints with elastomeric, thermosetting, or thermoplastic polymer adherends. The peel strength of cyanoacrylates is poor, they tend to be brittle, and they have limited temperature resistance. As a group, these adhesives are also poor at filling gaps, as they are very fluid.

5.4.5 Anaerobics

Anaerobic adhesives (or more properly, *anaerobic sealants)* are single-component monomeric liquids that harden satisfactorily only in the absence of gaseous oxygen (that is, without air). The mechanism is free radical polymerization. For this reason,

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[9] Silicon- (versus carbon-) based polymers (such as silicones) tend, as a group, to have higher temperature stability and tolerance, as we all know from the valid claims for "synthetic," silicon-based oils for automobile engines.

[10] It is important to remember this when using cyanoacrylates, because fingers, eyelids, lips, etc. can stick together very quickly and very firmly, until they are "unstuck" using warm water or other suitable solvents, preferably by medical personnel.

they must be stored in the presence of air, usually in permeable containers. As a group, these adhesives have exceptional fluidity and can easily flow into the smallest crevices, achieving thorough sealing when they are cured, with little or no shrinkage. One important application is in locking threaded fasteners to prevent unwanted loosening by vibration; this is one of the early applications that built Loctite its reputation as an adhesives manufacturer.

Second-generation anaerobics often contain some urethane to overcome inherent brittleness and improve peel and impact strengths. Shear strengths of up to 77.2 MPa (10 ksi) and temperature serviceability to 200°C (400°F) are possible.

5.4.6 Urethanes

Urethanes or *polyurethanes* are basically thermoplastic polymers that have the ability to develop cross-links under certain conditions, thereby making them fairly rigid thermosetting adhesives. One- and two-part systems, usually dissolved in solvents, are available. They are distinguished from epoxies by their inherent flexibility and high peel strengths.

Urethanes are generally applied to both adherends, which are then brought into contact when the proper tackiness is reached. Curing is usually done at room temperature and, while handling is possible immediately, full curing takes many hours or days. Heat can be used to soften the adhesive if it becomes too dry before bonding.

5.4.7 Silicones

Silicones are available as one- and two-component systems that cure to thermosetting solids. The one-component systems undergo acidic or nonacidic cure at room temperature when exposed to atmospheric moisture. (The acidic cure is what gives many silicone adhesives, sealants, and caulking compounds a distinct vinegar smell.) Two-component systems cure by condensation polymerization and are prone to polymerization reversion or decomposition.

Silicones have good peel strength over a wide temperature range (−60–250°C) (−75–480°F), and some can survive limited exposure to 370°C (700°F). Flexibility, impact resistance, and resistance to moisture, hot water, oxidation, and weathering are very good. Lap strengths tend to be poor, however.

As a group, silicone adhesives are expensive but versatile. They are able to bond metals, glass, paper, wood, thermosetting and thermoplastic polymers, and a wide variety of rubbers.

5.4.8 Hot Melts

Hot melt adhesives are copolymers of polyethylene with polyvinyl acetate, polyolefins, polyamides, polypropylene, nylon, polyester, and thermoplastic elastomers. They are

100% thermoplastic but are not composed entirely of polymers. A portion of most hot melts is diluent and/or filler. As a group, hot melts tend to soften noticeably at about 80°C (175°F), but are applied much hotter than that (e.g., 150–390°C (300–550°F)). Hot melts can be formulated to produce either rigid or flexible bonds and can attain 80% of their ultimate bond strength within seconds after application. They are excellent for bonding materials with either permeable or impermeable surfaces, and they are quite resistant to solvents and moisture. However, they do soften upon exposure to temperatures of 100–150°C (210–300°F). They are widely used by craftspeople (in glue guns) and carpenters. High-performance hot melts such as polyamides and polyesters can withstand limited loads at elevated temperatures without undergoing significant creep.

5.4.9 Phenolics

Phenolic adhesives (or more properly, *phenol–formaldehyde adhesives*) are widely used in bonding wood (e.g., making plywood) and thus are one of the most widely used of all of the synthetic structural adhesives. These adhesives rely on penetration of the pore or cell structure of the adherend (e.g., wood) to develop adhesion. Phenolics can also be used as primers for bonding metals. As a group, phenolics cure to thermosets.

In general, phenolics are very low-cost adhesives with good strength and resistance to biodegradation, hot water, and weathering. Elevated temperature resistance is also fairly good. Shortcomings include brittleness, low impact strength, and the development of high shrinkage stresses.

Phenolics are frequently combined with other polymers to produce alloys with one or more enhanced properties, such as higher bond strength, higher fatigue resistance, higher service temperature, and better resistance to water, humidity, salt, or weather. Examples include nitrile–phenolics, vinyl–phenolics, and epoxy–phenolics. Epoxy–phenolics offer excellent long-term service at 150–260°C (300–500°F), as well as good performance to −60°C(−440°F) if specially formulated.

5.4.10 High-Temperature Structural Adhesives

Perhaps the greatest shortcoming of many structural adhesives is their limited tolerance of elevated temperature (see Subsection 5.7.6). This shortcoming has been addressed by developing several special high-temperature structural adhesives. Most are based on synthetic organics having aromatic (i.e., benzene) and/or heterocyclic rings in their main molecule structure. Groups of polymers with such structures include polyimidazoles and substituted imidazoles. Both have open ring structures that close upon exposure to heat. Thus, they become stronger (as opposed to softening or decomposing) at quite elevated temperatures for polymers.

Two specific high-temperature structural adhesives are polyimide (PI) and polybenzimidazole (PBI). These are both expensive and difficult to handle in that they have long cure times and emit considerable volatiles (i.e., odors). Polyimides offer superior

long-term strength retention in air to 260°C (500°F), while polybenzimidazoles are stable to 288°C (550°F) for only short times. Both are prone to degradation by moisture. The principal use of such adhesives is in aerospace structures composed of metals bonded to metals or to composites, especially metal-matrix types.

Table 5.6 provides a summary of the principal characteristics of the major types of structural adhesives described above.

5.5 IMPORTANT INORGANIC ADHESIVES, CEMENTS, AND MORTARS

Among easily recognized natural adhesives, only sodium silicate (known as "water glass") is inorganic.[11] Even this one is, in reality, synthetic in that it is rarely, if ever, found in nature in a pure enough state to use as an adhesive, although it may be functioning as one where it is found (i.e., as a binding agent in minerals or aggregates of minerals). It must be processed to be a useful adhesive and, when it is part of a formulated system, it is clearly synthesized. "Cementitious" materials, as major components of mortars or used by themselves, are sulfate (SO_4)-, silicate (SiO_4)-, or phosphate (PO_4)-based inorganic adhesives made from naturally occurring minerals. They fall into two categories, "unfired" and "fired" cements. In their most common form, cements are not fired to cause sintering.[12] Some refractory cements, intended for very high-temperature service applications, are fired to sinter their individual ceramic particles into a solid aggregate. When firing and sintering are not involved, as in unfired cements, the process leading to bonding is called "cementation."

Let us look at some of the key mechanisms by which some major inorganic adhesives work and at some of the most important types.

In the case of sodium silicate, CO_2 gas is introduced to act as a catalyst to dehydrate the sodium silicate aqueous solution into a binding glass. The reaction is:

$$xNaO_2 \cdot ySiO_2 \cdot H_2O + CO_2 > \text{ glass}$$

In its most common application in making molds from sand for casting metals, liquid sodium silicate coats the SiO_2 sand grains and provides bridges between the sand grains. Introduction of CO_2 converts the bridges to a solid glass that joins the sand grains into a solid mold.

For elevated-temperature, refractory applications, such as cementing alumina bricks together to produce a furnace lining, fine alumina powder solutions are catalyzed with phosphoric acid to produce an aluminum phosphate cement by the reaction:

$$Al_2O_3 + 2H_3PO_4 > 2AlPO_4 + 3H_2O$$

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[11] In fact, there are other silicate-based, naturally occurring adhesives, with many being formed either as the excretions or decomposition products or residues of animals. The best examples are the calciferous cements found in coral that create reefs.

[12] *Sintering* is the formation and growth of material connections (or bonds) between and among particles of a material through solid phase diffusion at elevated temperatures to accelerate the diffusion kinetics.

Table 5.6 Summary of the Physical Characteristics of Major Organic or Polymeric Synthetic Structural Adhesives

Adhesive	*Type*	*Cure*	*Shear Strength MPA(ks)*	*Peel Strength N/m(1b/in)*	*Impact Resistance*	*Solvent Resistance*	*Moisture Resistance*	*Relative Price*	*Substrates Bonded*
Epoxies	One component	Heat							
	Two components	RT/heat	15.4 (2.2)	<525 (3)	Poor	Excellent	Excellent	Low	Most
	Film & tape	Heat + pressure							
Polyurethanes	One component	Heat							
	One component	Moisture	15.4 (2.2)	14,000 (80)	Excellent	Good	Fair	Moderate	Most, smooth & nonporous
	Two components	RT/heat							
Modified Acrylics	One component	RT/heat	25.9 (3.7)	5,250 (30)	Good	Good	Good	Moderate	Most, smooth & nonporous
Cyanoacrylates	One component	Moisture	18.9 (2.7)	< 525 (3)	Poor	Good	Poor	Moderate to high	Nonporous, metals or plastics
Anaerobics	One component	No oxygen	17.5 (2.5)	1,750 (10)	Fair	Excellent	Good	Moderate	Metals, glass & thermosets
Silicones	One component	Moisture	1.7–3.4 (0.25)	612 (3.5)	Good	Good	Excellent	Moderate to high	Most
Phenolics	One component	Heat							
	Two components	Heat	N/A	N/A	Fair	Good	Good	Low	Most
	Film & tape	Heat + pressure							
High-temperature	One component	Heat	8–14 (1–2)	N/A	Fair	Fair	Poor	High	Thermoplastics & metals
	Film & tape	Heat + pressure							
Hot-melts	One component	Heat	4.3 (0.6)	N/A	Fair	Fair	Good	Moderate to high	Thermoplastics & metals

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The aluminum phosphate cement bonds the alumina particles so they can withstand operating temperatures as high as 1,650°C (3,000°F).

In "plaster of Paris" (gypsum), which schoolchildren and modelers use to make sculptures, plasterers use to finish walls, and building material manufacturers use to make "dry board" or "plaster board," small particles (actually crystals) of $CaSO_4$ interlock into large crystals of gypsum ($CaSO_4 \cdot 2H_2O$) through hydration. The reaction is:

$$CaSO_4 \cdot \frac{1}{2}H_2O + \frac{3}{2}H_2O > CaSO_4 \cdot 2H_2O$$

The process of making gypsum involves "calcination" (dehydration) of $CaSO_4 \cdot 2H2O$ to $CaSO_4 \cdot \frac{1}{2}H_2O$ (plus $\frac{3}{2}H_2O$), while making plaster of Paris occurs by "rehydration" of $CaSO_4 \cdot \frac{1}{2}H_2O$ to $CaSO_4 \cdot 2H_2O$ (by adding $\frac{3}{2}H_2O$).

These and other cementitious materials are used to make certain unfired clay products.

By far the most important of all cements—technologically and economically—is "Portland cement."[13] A typical grade contains 19–25% SiO_2, 5–9% Al_2O_3, 60–64% CaO, and 2–4% FeO. This is seen in Figure 5.2, the simplified ternary phase diagram for the $CaO-SiO_2-Al_2O_3$ ceramic system.

The other major type of cement found in this system is "high-alumina cement," which consists of a mixture of mostly CaO and Al_2O_3 and offers quick setting (attaining the same strength in 24 hours that Portland cement attains in 30 days!). Typically, such high-alumina cement contains 35–42% CaO, 38–48% Al_2O_3, 3–11% SiO_2, and 2–15% FeO. Both types are manufactured by (1) grinding a proper mixture of clays and limestone; (2) firing the mixture in a kiln to produce a "clinker," and then (3) regrinding it to produce a fine gray powder.

Several minerals are present in Portland cement, including (1) tricalcium silicate, $3CaO \cdot SiO_2$ (called C_3S), (2) dicalcium silicate, $2CaO \cdot SiO_2$ (called C_2S), and (3)

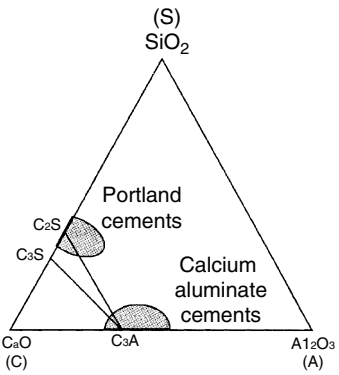

Figure 5.2 A simplified ternary phase diagram for the $CaO–Al_2O_3–SiO_2$ ceramic system showing the relative location of (a) Portland cements and (b) high-alumina cements. (Reprinted from *Engineering Materials and Their Applications*, R.A. Flinn and D.K. Trojan, Fig. 10.27, page 487, Houghlin Mifflin, Boston, MA, 1990, with permission.)

[13] "Portland cement" is named after the quarry in Portland, England where the natural limestone and clays used in its formulation were originally found.

tricalcium aluminate, $3CaO \cdot Al_2O_3$ (called C_3A). As shown in Figure 5.2, tetracalcium aluminum ferrite, $4CaO \cdot Al_2O_3 \cdot FeO$, is also present in the cement.

The reaction that forms the actual cement involves dissolution in water, recrystallization by hydration, and precipitation of a layered silicate structure made up of SiO_4 groups with Ca^{+2} and O^{-2} ions in the interstices and water molecules separating the layers held together by hydrogen bonding. Gypsum, $CaSO_4 \cdot 2H_2O$ (at about 2%) is added to retard setting and also reduce shrinkage by reacting with the tricalcium aluminate. The heat of reaction accompanying the adsorption of water arising during setting can be large and can damage a massive structure. Hence, newly cast cement structures are often continuously sprayed with water to slow setting, ensure ample water for hydration, and remove the heat of hydration. Low-heat grades can be made by reducing the amount of tricalcium aluminate.

Five grades of Portland cement are used in the manufacture of concrete, all given in Table 5.7. Composition among grades is modified to control the setting time and the heat of hydration. Lower water-to-cement ratio lead to higher compressive strength, which, as for all ceramics, is greater than tensile strength (as seen in Chapter 12). The most important use, by far, of Portland cement is in making concrete.

As stated earlier, mortars used in masonry are generally mixtures of lime (CaO) with water (H_2O) to form hydrated lime ($Ca(OH)_2$), which reacts with CO_2 to form $CaCO_3$ and sand (SiO_2) to form calcium silicate ($CaSiO_4$). The formation of the new crystals leads to bonding. A typical mortar (not unlike that given earlier in this chapter) consists of one part Portland cement, two parts hydrated lime, and eight parts sand, by volume.

As mentioned at the start of this section, there are also some "fired" cements intended for use at quite elevated temperatures. In these, the binding phase is usually a glass, which is itself a complex silicate network. More will be said about these in Chapter 12.

Table 5.7 The Five Grades of Portland Cement

ASTM		*Composition*[a] *(wt.%)*				
Type	*Characteristics*	C_3S	C_2S	C_3A	C_4AF	*Others*[b]
I	Standard	45	27	11	8	9
II	Reduced heat of hydration and increased sulfate resistance	44	31	5	13	7
III	High early strength (combined with high heat of hydration)	53	19	11	9	8
IV	Low heat of hydration (lower than II; especially good for massive structures)	28	49	4	12	7
V	Sulfate resistant (better than II; especially good for massive structures)	38	43	4	9	6

a. The shorthand notation used in the cement industry is: $C_3S = 3CaO \cdot SiO_3$; $C_2S = 2CaO \cdot SiO_3$; $C_3A = 3CaO \cdot Al_2O_3$; $C_4AF = 4CaO \cdot Al_2O_3 \cdot Fe_2O_3$

b. Primarily simple oxides (e.g., MgO, CaO, alkali oxides) and $CaSO_4$

Table 5.8 provides a summary of the principal characteristics of the major types of structural inorganic adhesives described on the previous page.

Table 5.8 Properties of Some Important Unfired and Fired Ceramic Cements and Inorganic Adhesives

Property	*Adhesive Cement*	*Electric-Heater Cement*	*Hi-Temp Cement*	*Electrotemp Cement*
Type set	Air	Air	Air	Chemical
Density (lb/in^3)	110	110	110	110
(gm/cc)	(1.76)	(1.76)	(1.76)	(2.56)
C.T.E.[a] in./in./°F	6.2×10^{-6}	6.5×10^{-6}	6.0×10^{-6}	2.6×10^{-6}
(cm/cm/°C)	(11.2×10^{-6})	(11.3×10^{-6})	(10.8×10^{-6})	(4.68×10^{-6})
Comp strength, psi	3900	2700	3500	5000
(kg/cm^2)	(274)	(189)	(246)	(316)
Dielectric constant	3.5–6.0	5.0–7.0	3.5–6.0	3.0–4.0
Dielectric strength, volts/mil (volts/mag)				
70°	12.5–51.0	12.5–51.0	12.5–51.0	76.0–101.5
(21°C)	(490–2000)	(490–2000)	(490–2000)	(2900–3900)
750°	15.0	15.0	15.0	25.0–38.0
(399°C)	(588)	(588)	(588)	(980–1490)
1475°F	1.3	3.8	1.3	12.5–25.0
(801°C)	(51)	(149)	(5.1)	(490–980)
Max service temp., °F	1800	2500	2500	2600
(°C)	(982)	(1370)	(1370)	(1426)
Modulus of rupture, psi	460	320	420	450
(kg/cm^2)	(32)	(22)	(29)	(31)
Shear strength, psi	710	300	600	365
(kg/cm^2)	(49)	(21)	(42.2)	(26)
Tensile strength, psi	410	285	400	250
(kg/cm^2)	(28)	(20)	(28.1)	(17)
Vol resistivity, ohm-cm				
70°F (21°C)	$10^8 - 10^9$	$10^7 - 10^8$	$10^8 - 10^9$	$10^{10} - 10^{11}$
750°F (399°C)	$10^4 - 10^5$	$10^4 - 10^5$	$10^4 - 10^5$	$10^9 - 10^{10}$
1475°F (801°C)	$10^2 - 10^3$	$10^2 - 10^3$	$10^2 - 10^3$	$10^8 - 10^9$
Thermal conductivity	4.7	5–8	7.0	10–12
$BTU/ft^2/hr/°F/in.$ $\frac{gm-cal}{sec-cm-°C}$	(1.6×10^{-3})	$(1.7-2.7 \times 10^{-3})$	(2.4×10^{-3})	$(3.4-4.1 \times 10^{-3})$
Resistance				
Acids	Yes, except hydrofluoric	Yes, except hydrofluoric	Yes, except hydrofluoric	No No
Alkalies	No	No	No	No
Water	Wash with acid	Wash with acid	Wash with acid	No
Oil	Yes	Yes	Yes	Yes
Electricity	Yes	Yes	Yes	Yes

[a] Coefficient of thermal expansion.

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Table 5.8 (*continued*)

Electrical-Insulating Cement	*Low-Expansion Cement*	*Acid-proof Cement*	*Electrical-Resistor Cement*	*Electrical Refractory Cement*
Chemical	Chemical	Chemical	Air	Hydraulic
160	141	121	116	156
(2.56)	(2.25)	(1.94)	(1.85)	(2.5)
3.1×10^{-6}	4.6×10^{-6}	6.3×10^{-6}	13.0×10^{-6}	8.0×10^{-6}
(5.58×10^{-6})	(8.28×10^{-6})	(11.3×10^{-6})	(23.4×10^{-6})	(1.43×10^{-6})
4000	3900	2200	3300	3500
(281)	(274)	(154)	(232)	(246)
3.0–4.0	5.0–7.0	5.0–7.0	3.5–4.5	–
–	25.0–51.0	12.5–38.0	12.5–51.0	–
–	(980–2000)	(490–1490)	(490–2000)	–
–	12.5–25.0	12.5–38.0	12.5–25.0	–
–	(490–980)	(490–1490)	(490–980)	–
–	1.3	2.0	7.5	–
–	(51)	(78)	–	
2200	1550	1750	2600	2600
(1204)	(843)	(954)	(1429)	(1429)
510	460	455	460	500
(35)	(32)	(32)	(32)	(35)
400	430	430	375	210
(28)	(30)	(30)	(26.4)	(15)
290	425	430	325	400
(20)	(29)	(28)	(22.8)	(28)
–	$10^7 - 10^9$	$10^9 - 10^{11}$	$10^8 - 10^9$	–
–	$10^4 - 10^6$	$10^7 - 10^8$	$10^5 - 10^6$	–
–	$10^2 - 10^3$	$10^2 - 10^3$	$10^3 - 10^4$	–
8–11	8	4–6	11	12
$(2.7 - 3.8 \times 10^{-3})$	(2.7×10^{-3})	$(1.4 - 2.0 \times 10^{-3})$	(3.8×10^{-3})	(4.1×10^{-3})
No	Yes, except hydrofluoric	Yes, except hydrofluoric	Yes, except hydrofluoric	Above pH 5
No	No	No	No	Yes
Yes	Yes	Yes	Wash with acid	Yes
Yes	Yes	Yes	Yes	Yes
Yes	Yes	Yes	Yes	Yes

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5.6 THE ADHESIVE BONDING PROCESS: STEPS AND EQUIPMENT

5.6.1 General Description of the Adhesive Bonding Process

Many factors must be considered when selecting a particular adhesive bonding method. These factors include (1) the size and the shape of the parts to be bonded; (2) the specific areas of the parts or adherends to which the adhesive is to be applied (and not applied); (3) the number of assemblies to be produced and the rate at which they are to be produced; (4) the viscosity and other characteristics (e.g., working time) of the adhesive; (5) the form of the adhesive; and (6) the requirements for setting or curing are all important.

The following sections take a brief look at each of the key steps in adhesive bonding, including adhesive storage, adhesive preparation, joint (or adherend) preparation, adhesive application, and joint assembly. In addition, the equipment needed to accomplish bonding is also described.

5.6.2 Adhesive Storage

The susceptibility of most adhesives, especially organic adhesives, to degradation by one or more environmental factors is well known. Extremes of temperature, humidity, water, solvents, and light (and other radiation) are but a few of the most important factors (see Subsection 5.7.6). As a result of this susceptibility, adhesives must be properly stored before their use.

Many adhesives, such as light-activated thermosetting types, must be stored out of the light or in dark translucent or opaque containers. Most should be stored at low temperature (e.g., 5°C (40°F)) to prolong shelf life (which means activity and potency). Anaerobic types need to be stored in the air, usually in permeable containers, as the deprivation of oxygen will promote cross-linking. Solvents and solvent-based adhesives, on the other hand, should be stored in impermeable containers that can be sealed quickly after use to prevent loss and the escape of toxic, irritating, unpleasant, or flammable fumes. In addition, storage areas for such adhesives should be well and properly ventilated so as to not pose environmental hazards. As a matter of common sense, resins and curing agents for thermosetting adhesives should be kept apart in storage to prevent accidental contamination should containers break.

The special requirements for storage (while important and not unreasonable) pose difficulties for many production environments, at least in terms of logistics (e.g., adhesives not being stored in the area where assembly occurs, or assembly not occurring close to where parts are prepared, etc.). Nevertheless, manufacturers' directions pertaining to storage should be carefully read and complied with.

5.6.3 Adhesive Preparation

Whenever adhesives are brought out of storage, they should be used as soon as practical, with unused material being returned to storage. The reasons for this,

depending on the specific adhesive, are to avoid loss of necessary but volatile solvents, absorption of undesirable moisture, exposure to intolerable light, warming to room temperature, and so on.

For adhesives that are refrigerated to retain shelf life, proper preparation means letting them reach application temperature and using them quickly. When separate components are to be mixed (e.g., the adhesive base and the hardener of a two-part thermosetting system), it is important to measure the proportions correctly to obtain optimum—and consistent—properties. Too little catalyst prevents proper polymerization of the resin, while too much catalyst can cause brittleness. Excess unreacted catalyst may also cause corrosion of the adherends, depending on what they are.

Mixing, whenever it is required, must be complete to assure homogeneity, and only enough adhesive should be mixed to allow working without curing (i.e., within the working life or "pot life" for that adhesive). While it must be thorough, mixing must also be done carefully to avoid foaming or excessive air entrapment, which can cause incomplete bonding in areas where gas bubbles settle onto the adherend. It may sometimes be necessary to degas a mixed adhesive under a light vacuum.

5.6.4 Joint/Adherend Preparation

As described in Chapter 4, it is essential that the surfaces of adherends to be bonded be cleaned completely and are kept clean until the adhesive is applied and the joint is assembled. To review what was described in Subsection 4.5.2: Cleaning can involve one or more of the following steps, in sequence, to whatever level is required to attain the degree of cleanliness needed: (1) solvent cleaning to remove oily or greasy contaminants and loose particulates; (2) intermediate cleaning with some combination of chemical and mechanical means to remove more tenacious contaminants or potential weak-boundary layers (e.g., oxide or other tarnish scales); and (3) chemical treatment to activate (or condition) the surface chemically and physically using more aggressive chemical agents (e.g., acid etching or pickling) or electrical or coronal discharge treatment.

Following whatever cleaning steps are necessary for the particular adherends, the cleaned surfaces must be protected from recontamination, including oxidation or adsorption of surface moisture (for some adhesives). Sometimes this is accomplished simply by covering the surface or "bagging" until actual assembly is accomplished. For longer delays before assembly or for some types of adhesives, a primer may be applied to the adherends' bonding surfaces. Recall that a primer is usually a dilute solution of the adhesive to be used, with some solvent. It is applied to the adherend surfaces to protect them from unwanted contamination after cleaning and, often, to precondition them for bonding with the adhesive when it is applied.

5.6.5 Methods of Adhesive Application

Selection of the method of adhesive application depends on the physical form of the adhesive being used. This, in turn, should depend on the size, shape, orientation,

and/or location of the parts to be bonded, the total surface area and specific locations to which the adhesive is to be applied, and the production rates and volumes to be achieved. Methods can be manual, semi-automated, or fully automated.

For liquid adhesives, methods of application include brushing, flowing, spraying, roll coating, knife coating, silk screening, squeeze application, and dipping. Brushing is best for complex shapes or selected area bonding without masks (i.e., areas covered to prevent the application of adhesive), where limited adhesive bond-line thickness control and slow application rates can be tolerated. Flowing is best for flat surfaces. It employs a nozzle or flow gun or hollow brush and is capable of providing a uniform film thickness. Spraying is good for large areas with gradual contours, so "runs" are not produced by the necessarily thin consistency of this form of adhesive application. Application rates can be high and film thickness control can be reasonably good, but there can be health hazards to be guarded against from mists and overspray. Roll coating uses a "pickup" roller with fluid adhesives, while knife coating uses a spreader (or "doctor") blade with thicker adhesives. Both methods are best for large, flat surfaces. Knife coating enables excellent control of film thickness through knife stand-off. Silkscreening involves applying the adhesive by filling pores with the desired pattern in an overlay screen. Areas on the adherend that are not to be coated with adhesive are blocked by the nonporous portions of the screen. Spot applications of adhesive can be made with a squeeze bottle or syringe, while very large surfaces can be covered by dipping, with or without masks, as appropriate.

More viscous paste adhesives can be applied by spreading with spatulas, knives (including doctor blades), and trowels. Dry powdered adhesives can be applied by sifting them onto preheated substrates, or by dipping the preheated parts with masks in areas that will not receive adhesive. Both methods ensure uniform coverage, since loose powder falls off and no spot is missed. It is also possible to apply dry thermoplastic adhesives by melting or, more properly, softening them into a paste or liquid and applying them as appropriate for those forms.

Film adhesives are, in many ways, the easiest to apply. The film form offers excellent repeatability (since no mixing is required), excellent thickness control, clean, easy, hazard-free handling, very little waste (when cut to size and shape preforms are used), and excellent properties in the final bond. As mentioned earlier, these films may be supported with a carrier or unsupported (i.e., adhesive only). Films are easiest to apply to flat surfaces or to parts with gradual, simple curves and contours. Complex or severely contoured surfaces make it difficult to get the films to lie flat without wrinkling and, thus, locally increasing the film thickness.

Finally, hot melts tend to be applied from melt reservoir systems or progressive feed systems, using various dispensing devices, such as applicator nozzles, syringes, or spreader blades.

5.6.6 Joint Assembly Methods

Assembly of the components of a structure or assembly to be bonded is often a complicated process. All components must be cleaned in the areas where adhesive is

to be applied and kept clean; adhesive must be applied where it is required, within the restrictions of its working life; components must be brought into proper location and orientation and kept there throughout setting or curing; and pressure and heat or drying must take place.

A number of methods have been developed for assembling joints for adhesive bonding, including (1) wet assembly using liquid adhesives, especially on porous adherends; (2) pressure-sensitive and contact bonding for adhesives that retain their tack when dry; (3) solvent activation (actually postponed wet assembly), except when unsuitable for nonporous adherends; (4) heat activation for thermoplastic adhesives; or (5) curing for thermosetting adhesives.

All of these methods have some common characteristics. The adhesive coating must become liquid at some point during assembly to promote contact with and ensure wetting of the adherends over the entire surface to be bonded (in accordance with Stefan's suggestions). Excess solvents or diluents (or both) must be able to escape from the bonding interface in the form of vapor or be absorbed somehow into the assembly or onto its surrounding materials, often called "scrim cloths." Volatile materials such as solvents and moisture must be expelled from the joint to prevent the formation of voids, vapor locks, and attendant faults in the glue line. This is often accomplished by providing venting features in the assembly tooling or the assembly itself. Pressure must be applied to the joint—over the entire surface area being bonded—until the adhesive has set sufficiently to hold the assembly together without accidental misalignment of the details.

5.6.7 Bonding Equipment

Once the proper adhesive has been properly applied to properly prepared adherends (which often includes providing some means of establishing and maintaining the bond-line thickness), the assembly must be mated as quickly as possible to prevent contamination of the adhesive and adherend surfaces. Then the substrates are held together under pressure and heated, if necessary, until the proper cure has been achieved. This latter step requires the use of equipment to control the adhesive thickness, apply pressure and, when required, apply heat.

Applying an adhesive layer that is uniform and of a controlled thickness is almost always required for sound structural joints. It is almost always desirable to have a uniformly thick (e.g., 0.05–0.5 mm (0.002–0.020 in.)) adhesive bond line. Three basic methods are used to control adhesive thickness. First, mechanical shims, spacers, or stops can be used. They can sometimes be removed after curing, but might have to be left in the cured assembly. If so, this must be considered and accounted for in the design. Shims are usually made of metal in the form of strips, wires, or even balls, with the strips almost always being removed, the wires rarely being removed, and the balls never being removed. A spacer or stop often is or could be an integral feature (e.g., a raised boss) on one of the components of the bond assembly. Second, a film adhesive can be used. Available in different starting thicknesses, these films become quite viscous during the curing cycle to prevent adhesive squeeze-out. Another possibility

is to use reinforcements in the adhesive that, because they are always solid, maintain the required spacing. Finally, trial and error can determine the correct pressure–adhesive viscosity combination that will yield the desired bond thickness. Trial and error, while widely practiced, should be avoided.

Pressure is always required to accomplish adhesive bonding, if for no other reason than to hold the components being bonded together until the adhesive sets (even if it has not fully cured). Pressure is also necessary to bring all areas of the faying surfaces into contact with the adhesive, to squeeze out air, and, for pressure-sensitive types, to activate the actual adhesion process. Pressure-applying devices should be designed to maintain uniform, constant, controlled pressure over the entire bond area throughout the entire setting or curing cycle. This usually means compensating for thickness reduction from adhesive flow-out and thermal expansion of the assembled parts. It also means accommodating the size and shape of the assembly. Popular types of pressurization systems include (1) pneumatic or hydraulic presses versus screw-activated mechanical presses, often with heated platens; (2) autoclaves, which apply isostatic pressure using air, gas (e.g., nitrogen or argon), or steam; and (3) vacuum bags, which allow the atmosphere to apply pressure up to atmospheric pressure (about 0.1 MPa or 14.7 psi) and, simultaneously, withdraw unwanted volatiles generated during curing or setting.

Figures 5.3 and 5.4 show autoclaves and a vacuum-bagging setup for applying pressure during adhesive bonding. Pressure distribution is usually accomplished in all of these systems using special bonding tooling.

For those adhesive systems that are activated and set or cured with heat, a means for applying controlled heat is also required. The heat needed to set or cure adhesives can be applied directly or indirectly to the assembly. Direct methods include ovens (for up to 450°C±1°C (842°F±1−2°F)), liquid baths (to 300°C (572°F) in silicone oils,

Figure 5.3 Typical large autoclaves used for performing adhesive bonding in the aerospace industry. (Courtesy of Northrop Grumman Corporation, El Segundo, CA, with permission.)

Figure 5.4 The use of vacuum bagging for applying pressure to an assembly during adhesive bonding of parts; in this case, co-curing and bonding of thermosetting-resin matrix composite parts of the inlet for an AX vehicle. (Courtesy of Northrop Grumman Corporation, El Segundo, CA, with permission.)

with comparable accuracy), or hot presses or platens (usually with somewhat less accuracy). Indirect methods include electric resistance heating, radiation curing (e.g., using infrared), high frequency dielectric or radio-frequency heating, induction heating, and ultrasonic activation.

With all these methods, precise control is critical since curing must be complete to obtain optimum properties. Modern manufacturing often calls for the use of embedded sensors for monitoring the state of the cure, perhaps using a measure of the adhesive's dielectric constant, and adaptively controlling the temperature according to the actual progress of the exothermic curing reaction in real time.

5.7 ADHESIVE-BONDED JOINT PERFORMANCE

5.7.1 General Description of Joint Performance Goals

Ultimately, an adhesive-bonded joint can only be judged by how well it performs in service. Attaining maximum performance in adhesive-bonded joints requires selecting the appropriate adhesive for the adherends and intended service conditions, employing proper bonding procedures, inspecting the bonded joint to ensure quality, and, at some point, testing bonded samples to verify performance.

The following subsections briefly consider the testing of adhesives and adhesive bonded joint properties, the assurance of joint quality by a combination of process control and inspection, the kinds of performance or properties that can be expected, and the effects of environment on joint durability.

5.7.2 Testing of Adhesives and Bonded-Joint Properties

Testing is important in materials science and engineering as a means of characterizing fundamental properties—during product and process development to optimize design and processing parameters, and in production to verify property attainment as an indication of process and quality control. Testing is especially important for adhesives, where many variables are critical to the ultimate performance of the bonded joint.

Tests are used, first and foremost, to evaluate the inherent strength of the adhesive. They are also used to evaluate the appropriateness of the joint geometry, the joint preparation technique (i.e., cleanliness, effectiveness of surface treatments, etching of surfaces), the adhesive application and coverage of surfaces to be bonded, and the effectiveness of the setting or curing cycle. Specific adhesive tests are used for various purposes. First, many are used to compare the properties of alternative adhesives, facilitating selection. Because of the ways in which adhesives can be loaded and fail, and because of their inherent sensitivity to environmental degradation (especially for organic types) and ability to be modified by alloying or through the addition of fillers, a great variety of properties needs to be assessed. Properties of interest include tensile, shear, peel, cleavage, impact, and flexural strength; fatigue strength and life; environmental durability (to a host of factors); and special properties (e.g., electrical or thermal conductivity). Second, some tests are used to check the quality of a lot or batch of adhesives to determine whether it is up to a standard. These tests are usually mechanical or physical but can be chemical in nature. Third, some tests are designed specifically to check the effectiveness of adherend and adhesive preparation. These are strictly mechanical in nature. Finally, some tests are designed to determine parameters important in predicting ultimate joint performance, such as curing or setting conditions and bond-line thickness.

Whatever the purpose, testing is almost always done in accordance with established standards, such as the standards and practices given by the American Society for Testing Materials (ASTM) or the Society of Aerospace and Automotive Engineers (SAE) in their Aerospace Recommended Practices (ARPs). This chapter will describe only the most common and important tests, and refers the reader to the specific standards (e.g., ASTM or SAE) or to various handbooks (Cagle (1973), Landrock (1985), for example) for more details. A summary of the most common standards and procedures used in testing adhesives and adhesive-bonded joints, extracted from several sources, is given in Table 5.9.

Tensile Tests

Tensile tests are the most common tests used to evaluate adhesives or any material. This is the case despite the fact that, for most adhesives, it is best to load them in pure shear. While most structural materials have tensile strengths that are high compared to structural adhesives, the advantage of conducting tensile tests on adhesives is that they generate fundamental and uncomplicated data in the form of tensile strain, tensile strength, and elastic or Young's modulus.

Table 5.9 Selected ASTM Test Methods and Practices for Evaluating Adhesives

Purpose	*ASTM Standard*	*Title*
Aging	D 1183	Resistance of Adhesives to Cyclic Aging Conditions
	D 3632	Accelerated Aging of Adhesive Joints by the Oxygen-Pressure Method
Biodeterioration	D 4299	Effect of Bacterial Contamination on Permanence of Adhesive Preparations and Adhesive Films
	D 4300	Effect of Mold Contamination on Permanence of Adhesive Preparations and Adhesive Films
Chemical Reagents	D 896	Resistance of Adhesive Bonds to Chemical Reagents
Cleavage	D 1062	Cleavage Strength of Metal-to-Metal Adhesive Bonds
	D 3807	Strength Properties of Adhesives in Cleavage Peel by Tension Loading (Engineering Plastics-to-Engineering Plastics)
Corrosivity	D 3310	Determining Corrosivity to Adhesive Materials
Creep	D 1780	Conductivity Creep Tests of Metal-to-Metal Adhesives
	D 2293	Creep Properties of Adhesives in Shear by Compressive Loading (Metal-to-Metal)
	D 2294	Creep Properties of Adhesives in Shear by Tension Loading
Cryogenic	D 2557	Strength Properties of Adhesives in Shear by Tension Loading in the Temperature Range from −267.8 to −55°C (−457 to −67°F)
Durability	D 1151	Effect of Moisture and Temperature on Adhesive Bonds
	D 1828	Atmospheric Exposure of Adhesive Bonded Joints and Structures
Fatigue	D 3166	Fatigue Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)
Flexural Strength	D 1184	Flexural Strength of Adhesive Bonded Laminated Assemblies
High Temperature	D 2295	Strength Properties of Adhesives in Shear by Tension Loading at Elevated Temperatures (Metal-to-Metal)
Impact Strength	D 950	Impact Strength of Adhesive Bonds
Low and Cryogenic Temperature	D 2557	Strength Properties of Adhesives in Shear by Tension Loading in the Temperature Range from −267.8 to −55°C (−450 to −67°F)
Peel Strength	D 903	Peel or Stripping Strength of Adhesive Bonds
	D 1781	Climbing Drum Peel Test for Adhesives
	D 1876	Peel Resistance of Adhesives (T-Peel Test)
	D 3167	Floating Roller Peel Resistance
Radiation Exposure	D 904	Exposure of Adhesive Specimens to Artificial and Natural Light
	D 1879	Exposure of Adhesive Specimens to High-Energy Radiation
Salt Spray	B 117	Salt Spray (Fog) Testing
	G 85	Modified Salt Spray (Fog) Testing
Shear Strength	E 229	Shear Strength and Shear Modulus for Structural Adhesives
	D 905	Strength Properties of Adhesive Bonds in Shear by Compressive Loading
	D 1002	Strength Properties of Adhesives in Shear by Tension Loading (Metal-to-Metal)
Tensile Strength	D 897	Tensile Properties of Adhesive Bonds
	D 2095	Tensile Strength of Adhesives by Means of Bar and Rod Specimens

Compiled from multiple sources, including references and handbooks by ASM International, Cagle, Landrock, and Pocius (see reference sections for Chapters 4 and 5).

Tests of pure tension are those in which the loading is applied absolutely normal to the plane of the bond line and in line with the center (i.e., the centroid) of the bond area as shown in Figure 4.10. The original ASTM test method is D 897, which is shown below as a single example of such a standard.[14]

> ASTM D 897—Standard Test Method for Tensile Properties of Adhesive Bonds, 5 pp (DoD Adopted)
>
> This method covers the determination of the comparative "butt" tensile properties of adhesive bonds tested on standard-shape specimens under defined conditions of pretreatment, temperature, and testing machine speed. The method is known as the "butt" joint adhesion tensile test. The method is not as commonly used as the lap-shear test (ASTM D 1002). Blocks or rods of wood or metal are shaped or machined to specified dimensions of 1-$\frac{13}{16}$ in. (46 mm) diameter for wood or 1-$\frac{7}{8}$ in. (47.5 mm) for metal for the contact surface. The wood specimens are made from hard maple, and the metal specimens may be brass, copper, aluminum, steel, phosphor bronze, magnesium, or nickel silver. Two of the machined circular contact surface buttons are bonded together with the adhesive under test. A tensile testing machine is used under standardized conditions, and the maximum load at failure is recorded with the force normal to the contact area. The wood specimens must be conditioned at 23°C (73.4°F) and 50% RH, but no preconditioning is required for the metal specimens. Results are reported in pounds per square inch (psi) and kilograms per square millimeter (kg/mm^2). (This method replaces Federal Test Method Standard No. 175a, Method 1011.1).

Shortcomings in the original specimen and grips led to revised designs and methods, appearing in ASTM D 2094 and 2095.

Shear Tests

Shear tests are quite common because specimens are simple to fabricate and clearly duplicate the geometry and service conditions imposed on many structural adhesives when they are being used properly. As with tensile tests, the stress distribution is not uniform (see Figures 4.13 and 4.16), and while it is conventional to give the failure shear stress as the load divided by the bonding area, the maximum stress at the bond line may be considerably higher than the average stress, and the stress in the adhesive may differ from pure shear. The actual failure of the adhesive shear joint can be dominated by tension or shear, depending on the adhesive thickness, the stiffness of the adherends, and so on.

Pure shear stresses are those that are imposed perfectly parallel to the bond line and in the plane of the adhesive. While they do not produce pure shear, plain single-lap flat shear specimens are frequently used because they are simple to prepare and provide reproducible and usable results. The preparation of the specimens and the method of testing are described in ASTM D 1002. Several variations are also used, as shown in Table 5.9.

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[14] This standard is used with permission of the ASTM.

Peel Tests

Peel tests are designed to measure the resistance of adhesives, especially highly flexible ones, to localized stress (see Figure 4.13b) and failure by progressively opening the joint out of plane. The less rigid the adherend and the higher the modulus of the adhesive, the more nearly uniform the stress distribution will be in the adhesive. Because the area over which the stress acts is dependent on the thickness of the adherends and the adhesive, it is very difficult to evaluate exactly. Therefore, the applied stress and the failing stress are reported as linear values (pounds per linear inch (pli) or newtons per millimeter (N/mm)). The most widely used peel test, especially for thin-gauge metal adherends, is the T-peel test, which is covered by ASTM D 1876. Other peel tests are also covered by ASTM standards for various other situations (see Table 5.9).

Cleavage Tests

As described in Chapter 4 and shown in Figure 4.11, cleavage is a variation of peel. In the case of cleavage, however, the two adherends are rigid rather than flexible. The cleavage test, covered by ASTM D 3807, is designed to measure the effect of a load that is applied normal to the bond area at one end of the specimen.

Creep Tests

When a bonded structure is subjected to a sustained load in service, especially when the service temperature is somewhat elevated (i.e., approaching or exceeding the glass transition temperature of a polymeric adhesive) and/or the loading is vibrational, it is important to measure the resistance of the adhesive to creep. ASTM D 1780 covers the procedure for conducting creep tests on adhesives, with the special cases of compressive loading being covered by ASTM D 2293 and tensile loading by ASTM D 2294.

Fatigue Tests

Intermittently or cyclically applied loads impose an especially rigorous condition on adhesives, just as they do on most materials. For this reason, a special test method, covered by ASTM D 3166, is used. This test employs the plain single-lap shear specimens from ASTM D 1002. The specimen is tested on a standard tensile-testing machine capable of imposing cyclic (e.g., sinusoidal) loads, usually at 1,800 cycles per minute. Adhesive performance is evaluated from a plot of the number of cycles necessary to cause failure at various stress levels, using a so-called "S-N curve."

Impact Tests

If an adhesive-bonded joint is expected to experience impact or shock loads, it should be tested under such loading conditions, according to ASTM D 950. Here, the ability of the adhesive to absorb or attenuate impulse forces quickly is assessed, measuring the rate sensitivity of the adhesive to such applied loads. Results are reported as the number of foot-pounds (or newton-meters) of energy absorbed by a falling weight, simply under the force of gravity, while others use compressed air to accelerate the weights.

Durability Tests

As will be described in Subsection 5.7.6, the performance of adhesive-bonded joints in service can be significantly degraded by environmental factors. Therefore, it is critically important to evaluate the durability of adhesives and adhesive-bonded joints under the types of environments expected in service.

While there are a number of different tests for evaluating specific environmental effects, the most important is the wedge test, covered by ASTM D 3762. In this test method, a wedge is forced into the bond line of a flat-bonded aluminum specimen, thereby creating a tensile stress in the region of the resulting crack tip. The stressed specimen is then exposed to the appropriate representative environment (e.g., water or moisture at elevated temperature), and the resultant rate of crack growth with exposure time, as well as the ultimate failure mode, is evaluated. While the test is primarily qualitative, it is useful for determining preferred adhesive choices and joint preparation methods.

Similar tests exist for testing cements and mortars. These are covered in detail in specific references on these materials (as well as concrete) used extensively by civil engineers. Table 5.10 provides a summary, just for convenience rather than completeness.

5.7.3 Quality Assurance in Adhesive Bonding

One of the more frustrating disadvantages of adhesive bonding as a joining process is that the bond area cannot be inspected visually, making an assessment of the quality of

Table 5.10 Summary of Important Tests for Evaluating Cement and Concrete

General:

- "Standard Methods of Sampling and Testing Concrete Masonry Units" (ASTM C140)
- "Test Method for the Compressive Strength of Hydraulic Cement Mortar" (ASTM 109)
- "Standard Test Method for Splitting Tensile Strength of Masonry Units" (ASTM C1006)

Specific Tests:

• Biaxial Strength	To assess failure modes versus different combinations and directions of principal stresses
• Compressive Strength	To assess strength under shear compression of prisms [of cement] with low height-to-thickness ratios (<2:1)
• Diagonal Compressive Strength (ASTM 1391)	To determine the capacity of masonry under conditions that can produce diagonal cracking (see Biaxial Strength)
• Fire Resistance (ASTM E119)	To assess the effect of fire on the structural integrity of cement and mortar
• Flexural Strength (ASTM 1390 and ASTM C1072)	To assess the response of masonry structures to out-of-plane bending due to wind, earth movement, etc.
• Freeze-Thaw	To assess the durability of masonry under cyclic freezing and thawing
• Racking	To assess the response to an offset or eccentric vertical compressive load

the joint difficult. This continues to limit use of adhesive bonding in more demanding applications. Typically, assuring quality during adhesive bonding and of the bonded joints is carried out by two broad approaches: (1) destructive testing using process control coupons and (2) nondestructive evaluation involving joint assessment or inspection. Obviously, the level of quality control applied to a particular bonded assembly rightly depends on its structural requirements and criticality to overall system performance and/or safety. Critical joints are controlled by high sampling levels for destructive testing and by tight acceptance requirements. Less critical joints are controlled by less stringent procedures.

Destructive testing as a means of inspection is carried out on process control specimens prepared from the same adherend and adhesive materials, using the same procedures as the production parts. The process control specimens, as the name implies, accompany the production parts throughout all stages of production—from joint cleaning through assembly to curing. The adhesives and adherends in the process control specimens and in the production parts are all assembled at the same time, in the same environment, by the same production worker(s) or automated systems, and are cured in the same press or autoclave or vacuum-bagging run. As an additional control, expendable tabs or protrusions are often used on the actual production parts for subsequent removal and testing with the process control specimens. Test results are then checked against and compared with the specification requirements, and the part is accepted or rejected based on these results. The rejected parts may be subsequently inspected nondestructively for final acceptance or rejection, under discrepancy or discrepant part procedures.

During processing, quality control procedures should be applied at various stages, beginning with receipt of incoming raw materials (e.g., adhesives and adherends). Incoming inspection should (at minimum) include assessing the condition of the container in which the adhesive or adhesive constituents are received; looking for damage and/or leakage; checking the identity of the adhesive or constituents; and conducting appropriate tests on physical properties (such as percent flow, gel time, and percent volatiles) and mechanical properties. This should be done for each individual batch or lot of raw material. Second, quality control procedures should accompany adherend surface preparation. This involves ensuring that the proper solvent cleaning, intermediate cleaning, chemical/mechanical treatment, and priming steps and procedures have taken place, monitoring the proper identity, sequence, and purity or cleanliness of materials used, solution temperatures and concentrations, and checking cleanliness using wetting tests such as the water break-free test (see Figure 4.9). Also, once properly cleaned and prepared, the adherend surfaces should be properly protected to maintain cleanliness. Third, quality control procedures should be applied during bonding. Here, inspection should ensure the proper prefit of components to be bonded using tool-proofing films to produce an image or imprint of the joint high and low spots; verify the presence of required process control specimens; verify proper adhesive application (including complete coverage and checking of thickness, if important); and verify proper assembly to ensure that all required parts have been assembled in the correct location and sequence. Finally, quality control should accompany the setting and, especially, curing, stage. Here, inspection should verify that the proper

temperature-pressure-time cycle was employed, ideally using sensors embedded in the production parts or assembly to permit real-time monitoring and adaptive control.

After assembly bonding, it is essential to test process control specimens to ensure compliance with specifications, and to inspect the joint nondestructively. The tests and testing procedures to be used were discussed in the previous subsection. Nondestructive inspection techniques could and should include visual inspection and various sonic, ultrasonic, thermographic, and radiographic techniques. Brief descriptions of some of the more important and common techniques are given in the various titled paragraphs that follow.

Visual Inspection

Even though the adhesively bonded area cannot be observed directly as mechanical fasteners and most welds can, many indications of poor bonding may be evident. By using a strong light, directed at a shallow angle of incidence to the external surface of the bonded parts to highlight features in relief, one can check surface smoothness as an indication of unbonded areas. Such areas often show as bumps or waves in thin adherends. It is also possible to observe the bond line around the perimeter of the bonded parts, observing its thickness (noting whether it is too thick or too thin), the absence of adhesive (perhaps indicating too low a clamping force or insufficient adhesive), and adhesive "flash" (from squeeze-out) that breaks away from the adherend too easily (perhaps indicating poor surface preparation), noting whether it is excessively porous (indicating either gas entrapment, outgassing, or decomposition from overcuring) or is too soft or softens with solvent or heat (indicating improper curing of thermosetting types).

Sonic Methods

Tapping with coins or a solenoid-operated hammer can detect large voids or unbonded areas.[15] Properly bonded regions produce sharp, clear tones, while large areas devoid of adhesive or not bonded produce dull, hollow tones. Sonic resonators sense deflection of the adherend, which is greater in unbonded or weakly bonded regions than in properly bonded regions. These resonators employ a vibrating crystal to excite the structure acoustically at some frequencies between 5 and 28 kHz. Various eddy-current methods can induce mechanical forces in the bonded or unbonded structure through the induced electric fields. The result is an eddy-current test method.

Ultrasonic Methods

Ultrasonic methods are acoustic methods based on the response of the bonded joint to loading by low-power ultrasonic energy. The methods are excellent for detecting

[15] There are actually two different causes of unbonded regions. The first is called a "debond." Here, bonding never occurred. The second is called a "disbond." Here, bonding did occur but, because of something improper in adhesive selection, adhesive or adherend preparation, or curing, it separated before inspection.

unbonded regions between the face sheet and the adhesive, the adhesive and the core in honeycomb[16] sandwich structures, or between the adhesive and the adherends in laminated structures. Both pulse-echo (i.e., a "send–receive" approach using the same transducer) or through-transmission (i.e., a "pitch-catch" approach using a transmitting and receiving transducer) modes can be used. The most well known and highly regarded method is the Fokker bond method, which employs a sweep frequency resonance technique. Here, the ultrasonic energy introduced into the structure is varied over a wide frequency range. The resonance set up by the probe, face sheet, adhesive, and the remainder of the structure is monitored. Changes in loading are shown by the combination of a resonance-frequency shift and change in amplitude at the resonant frequency. Together, these give a semi-quantitative estimate of the bond strength, as affected by the presence of voids, porosity, and incomplete wetting.

Dynamic Thermal Imaging (or Thermographic) Methods

With dynamic thermal imaging methods, bond discontinuities are revealed through temperature differences that arise during either the heating or cooling of assemblies due to differences in thermal diffusivity in intimately bonded and unbonded areas. Cholesteric liquid crystals (which exhibit color changes with small temperature changes), infrared sensing, and other techniques are used.

Radiographic Methods

Radiographic methods, as opposed to all the previously described methods, permit direct imaging of defects in the adhesive–adherend interface under certain circumstances. X-rays can be used if the adhesive contains a metal or other filler that absorbs the x-rays. Radioisotopes can be used to determine whether electrolytes marked with a radioactive tracer penetrate a bonded joint. Neutron radiography can be used where the adhesive is not absorptive to x-rays. Hydrogen atoms in the adhesive absorb neutrons, making polymeric adhesives radio-opaque and allowing detection of any defects.

In conclusion, proper quality assurance of the adhesive-bonding process involves careful process control, largely through monitoring all stages of the process, as well as using process control specimens to permit destructive testing of representatives of the bonded assembly, and through nondestructive inspection of the final assembly.

5.7.4 Typical Properties of Organic Adhesives

It is not the intent of this book to provide a comprehensive reference for the properties of adhesives or adhesive-bonded joints (or for any other joining method, for that matter). Rather, it is intended to provide a comprehensive overview of all methods

[16] "Honeycomb" is a special ultra-lightweight, strong and stiff structure made by creating hexagonal, beehive-like cells through the thickness direction (which can be considerable). It is made by either adhesive bonding or, for high-temperature applications, brazing thin (foil-gauge) sheets along lines that stagger from layer to layer or ply to ply. The stackup is then expanded to create the honeycomb, which resembles corrugated cardboard in its appearance and its method of manufacture.

for joining materials and structures, with comparisons between processes, along with elucidation of the challenges posed by various materials and structures to processes of joining. This being said, it is nevertheless useful to describe some of the more important properties of some of the more important adhesives, to give an indication of what kind of performance can be expected.

Table 5.11 presents a compilation (from many sources) of the room-, low-, and high-temperature shear and peel strengths of several common and important organic adhesives.

As will be discussed in the next subsection, the properties of adhesives (particularly, but not only, organic types) vary considerably depending on the environment, with temperature and humidity being major factors. Other property data for low temperatures, for high temperatures, and after exposure to humidity will be presented in Subsection 5.7.6, and some additional data is presented in Section 5.4 for individual types of organic adhesives. The interested reader is referred to any one of several excellent handbooks on adhesives listed at the end of this chapter for more comprehensive and detailed property data.

5.7.5 Typical Properties of Important Cements and Concretes

Because cements and mortars used in masonry are without a doubt the most important of all adhesives (as exemplified in Figure 5.5), it would be a mistake not to include any property data on them. Table 5.12 summarizes some of the most important properties for some of the most important of these inorganic adhesives, as well as the concretes they are most often used to produce.

5.7.6 Effects of Environmental Factors on Adhesives and Adhesive-Bonded Joints

Adhesive bonds must withstand the mechanical forces that act on them, but they must also resist the environment in which they must serve. The nature of virtually all adhesives is that they are prone to environmental degradation from many and diverse sources. Common environmental factors that can degrade the performance—and life—of adhesives are (1) temperature that is too high or too low; (2) moisture in the form of water or humidity; (3) solvents or corrosive agents (which tend to be worse for organic adhesives if they are organic or for inorganic adhesives if they are inorganic)[17]; (4) excessive dryness; (5) weathering (which involves cyclic heating and cooling and moistening and drying); (6) radiation (including light, but especially gamma rays, thermal neutrons, etc.); and, for some types, (7) biological agents. Most natural adhesives are especially prone to degradation by temperature and moisture, but some are absolutely water resistant (like the adhesive produced by mussels and barnacles). Applied stresses usually accelerate degradation of adhesives for any particular environmental factor.

[17] This is in accordance with the useful adage, "Like dissolves like," taught in every chemistry course.

Table 5.11 Important Properties for Major Structural Organic or Polymeric Synthetic Adhesives

Adhesive	*Service Temperature Range °C (°F)*	*R.T. Shear MPa (psi)*	*R.T. Peel N/m (lb/in)*	*Low T Shear MPa (psi)*	*Low T Peel N/m (lb/in)*	*High T Shear MPa (psi)*	*High T Peel N/m (lb/in)*
Acrylics		28.4 (4,000)					
Anaerobics	−54 to 232 (−65 to 450)	77.2 (10,000)					
Cyanoacrylates	−54 to 77 (−65 to 170)	13.7 (2,000)					
Elastomerics	66 to 93 (150 to 200)	0.21 to 1.23 (30 to 180)	98.1 (0.56)				
Epoxies	−150 to 260 (−250 to 500)	15.4 (2,200)	525 (3.0)	9.5 (1,000)		5.1 (750)	
Epoxy–phenolics	149–370 (300 to 700)	14–22 (2,000–3,200)	1,050–2,100 (6–12)	14.0 (2,100)		3.3 (450)	
Ethylenevinyl–acetates	−35 to 80 (−30 to 175)						
Hot–melts	−55 to 82 (−67 to 180)	3.4–4.3 (500–630)	5,250 (30)	28.2 (4,100)	700 (4)	2.8 (400)	3,500 (20)
Modified acrylics	−110 to 177 (−160 to 350)						
Natural rubber	−35 to 70 (−30 to 160)						
Neoprene	−50 to 95 (−60 to 200)	0.2–2.0 (30–290)					
Neoprene–phenolics	−57 to 93 (−70 to 200)	14–35 (2,000–4,750)	1,700–10,000 (10–59)				
Nitrile–epoxies		24.5–44.7 (3,550–6,480)					
Nitrile–phenolics	−57 to 150 (−70 to 300)	21–31 (3,000–4,500)	2,625–10,500 (15–60)	19–22 (2,800–3,000)		10 (1,400)	
Nitrile rubber	−50 to 150) (−60 to 300)	1–14 (150–2,000)					
Nylon–epoxies	−240 to 125 (−400 to 250)	34–49 (5,500–7,200)	14,000–26,000 (80–150)	31.7 (4,600)	700 (4)	4.2 (600)	
Phenolics	to 140 (to 280)	7–28 (1,000–4,000)				to 7 (to 1,000)	
Phenoxy	−62 to 82 (−52 to 180)	17–27.5 (2,465–4,000)	3,152–5,225 (18–20)	21 (4,200)		9 (1,350)	
Polyamides	−40 to 185 (−40 to 365)	7.7 (1,000)		22 (4,000)			
Polybenzimidazole	to 288 (to 550)	14.5 (2,000)					
Polyimides	−196 to 540 (−330 to 1,000)	19 (2,800)	4,300–5,300 (25–30)	29 (4,200)		6 (850)	
Polysulfanes	−101 to 149 (−150 to 300)	27.5 (4,000)					
Polyurethanes	−240 to 127 (−400 to 260)	12–16.6 (2,000–2,400)		55.2 (8,000)	4,550 (26)	2.2 (318)	
Polyvinyl–acetals	0 to 120 (30 to 250)	14 (2,000)					
Silicones	−73 to 260 (−100 to 500)	1.7–3.4 (250–500)	1,700–3,200 (10–19)	3 (500)		2 (300)	
Styrenebutadienes	−40 to 70 (−40 to 160)						
Vinyl–phenolics	−60 to 100 (−70 to 212)	21–31 (3,000–4,500)	2,635–6,065 (15–35)	20 (2,900)		20 (2,900)	
Epoxy–polyurethanes	−73 to 121 (−100 to 250)	15 (2,000)	38,700 (210)	4 (600)	26,000 (150)	2.2 (330)	8,600 (50)
Epoxy–polysulfides	−100 to 50 (−150 to 125)	6–17 (1,000–2,500)	1,400–3,200 (8–19)				

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 173, Table 5.5, 1993, with permission Elsevier Science, Burlington, MA.

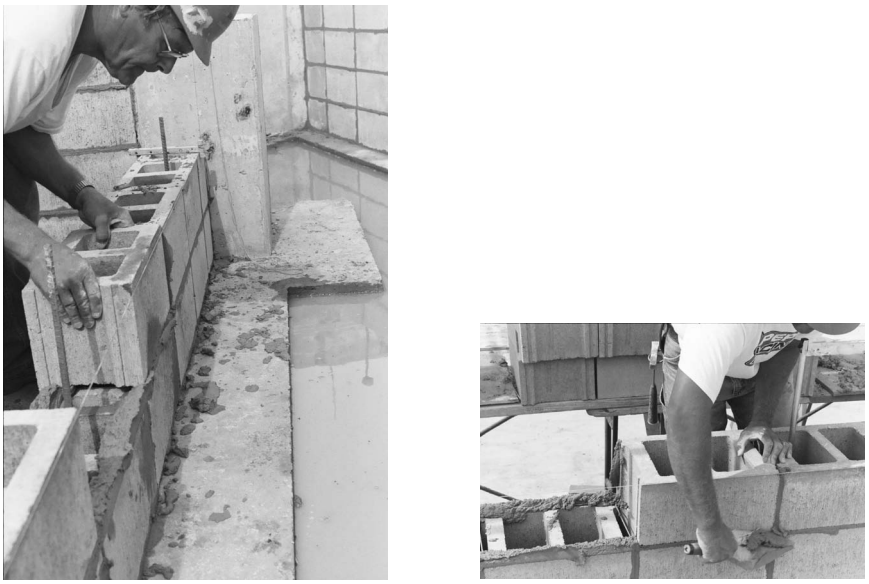

Figure 5.5 The construction of a cement or concrete block wall using a common Portland cement–lime–sand mortar. (Courtesy of the National Precast Concrete Association, Indianapolis, IN, with permission.)

Individual environmental factors are discussed briefly in the following titled paragraphs.

High Temperature

All polymers and, therefore, all polymeric adhesives are degraded to some extent by exposure to elevated temperatures. Mechanical and physical properties are degraded at elevated temperatures and after continuous or repeated exposure to elevated temperatures.

For an adhesive to withstand high temperatures, it must have a high melting or softening or decomposition temperature and must be resistant to oxidation. Thermoplastic adhesives perform well up to their glass transition temperature, T_g (see Chapter 13, Section 13.1), at which point the cohesive strength between long-chain molecules arising from secondary bonding degrades rapidly and the polymer softens or becomes less viscous. In general, thermoplastic adhesives have more limited elevated temperature resistance than thermosetting types, typically less than 120°C (250°F). The best-performing thermoplastic adhesives, in terms of temperature serviceability, are the hot-melt polysulfones. Typical strengths as a function of temperature for a variety of liquid, paste, tape, film, and solvent-based structural adhesives are shown in Figure 5.6.

Table 5.12 Summary of Important Properties of Major Cements and Concretes

Properties of Portland Cement (ASTM C150): 147–150 lb/ft^3 or 2435 kg/m^3

28-day Compressive Strength	3,000–5,000 psi (20–35 MPa)
Elastic Modulus	$4-22\times10^6$ psi (30–150 GPa)
Approximate Tensile Strength	580 psi (4 MPa)
Approximate Fracture Toughness	6.4 ksi/in. (0.5 MPam$^{-1/2}$)
Compressive Creep Strength	500–700 mm reduction in length (after 250–350 days at 600 psi or 4.14 MPa)
Thermal Conductivity	3.15–5+ BTU/hr/in.

Compressive Strength (psi, after 28-day cure)

	Water:Cement Ratio				
	0.3	0.4	0.5	0.6	0.7
Non-air-entrained Type I (Normal) Concrete	–	5,900	4,700	3,750	3,000
Air-entrained Type I (Normal) Concrete	–	4,800	3,650	2,750	2,400

Fraction of Compressive Strength Developed (Normalized against Type I Portland cement) for Different Portland Cements

	Cure Times (days)			
	1	7	28	90
ASTM Grade I	1.0	1.0	1.0	1.0
ASTM Grade II	0.75	0.85	0.90	1.0
ASTM Grade III	1.90	1.20	1.10	1.0
ASTM Grade IV	0.55	0.55	0.75	1.0
ASTM Grade V	0.65	0.75	0.85	1.0

Adhesives that are resistant to high temperatures are either thermosetting polymer types that have rigid, cross-linked structures and high softening or, more often, decomposition temperatures, and stable chemical side groups or radicals, or they are inorganic. Thermosetting polymeric or organic adhesives have no real melting point, although they do still have a T_g, and thus perform well to relatively high temperatures for polymers, provided thermal oxidation and pyrolysis are avoided. While few thermosets can withstand long-term service over 177°C (350°F), some recently developed types can withstand sustained exposure to approximately 320°C (600°F), with limited excursions to 370°C (700°F). Epoxy adhesives are usually limited to applications below 120°C (250°F), but some can tolerate short-term service to 260°C (500°F) and long-term service from 150–260°C (300–500°F). Silicones are good to 260°C (500°F) long term and 320°C (600°F) short term, while epoxy-phenolic alloys can operate successfully to 370°C (700°F). The polyimide (PI) and polybenzimidazole (PBI) adhesives are the best when it comes to temperature tolerance, operating at over 540°C (1,000°F) for short intervals, with good thermal stability (see Figure 5.6) but poor tolerance for moisture.

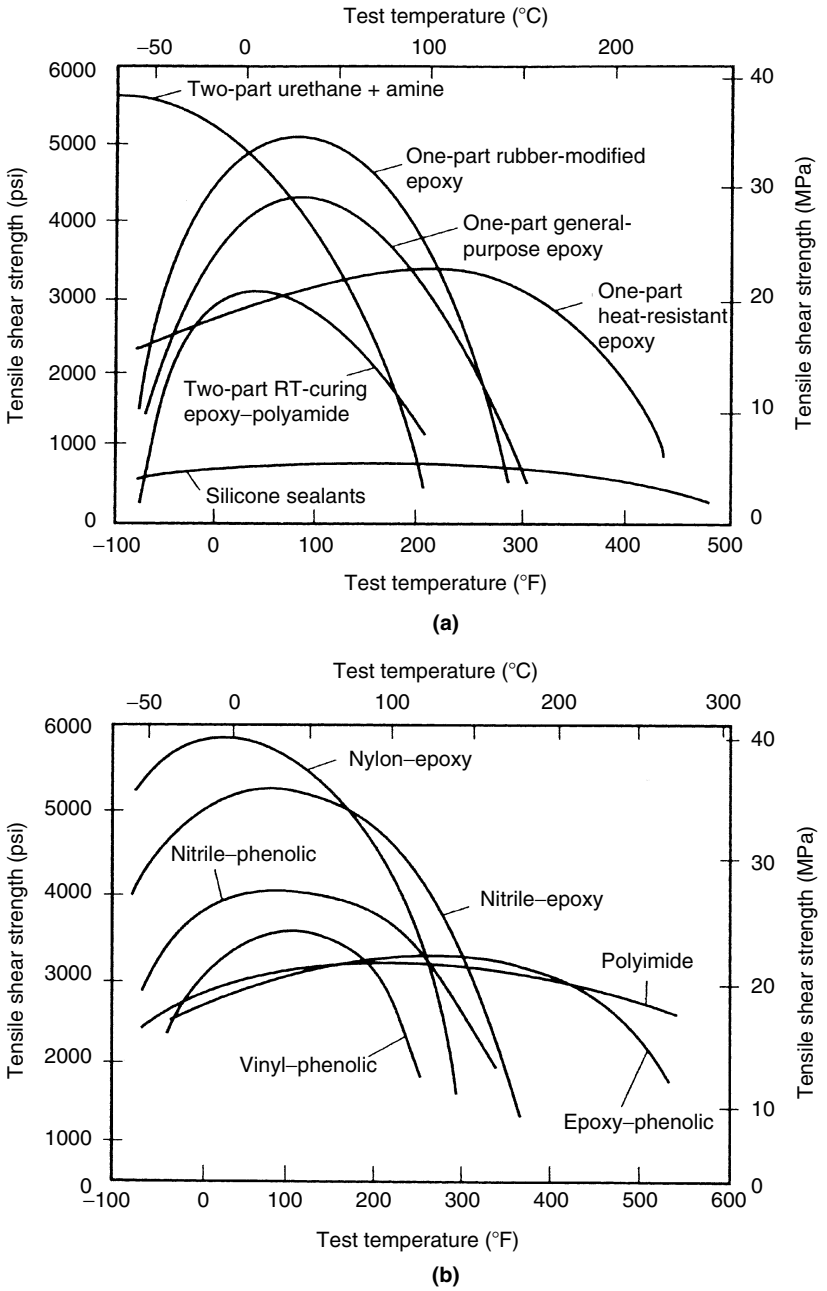

Figure 5.6 A plot of the tensile shear strengths of some structural organic adhesives as a function of temperature: (a) paste and liquid adhesive; (b) tape-, film-, and solvent-based adhesive. (Reprinted from *Adhesives Technology Handbook*, A.H. Landrock, Figures 5.1 and 5.2, pages 151 and 152, Noyes Publications, Park Ridge, NJ, 1986, with permission.)

Most cements used in construction, notably Portland cements, have rather limited tolerance to elevated temperatures, while the high-alumina cements can tolerate much higher temperatures. Likewise, there are other cements intended for use with refractory bricks and these, too, can tolerate high temperatures. Table 5.12 lists some service temperatures and strengths for some important types of cement. The mechanism by which so-called "hydraulic cements" fail at elevated temperature is loss of their waters of hydration (typical at around 400°C or 700°F, and which in turn leads to loss of bonding between particles in the cement.

Low and Cryogenic Temperatures

"Cryogenic adhesives" have been defined as those capable of retaining shear strengths above 6.89 MPa (1,000 psi) at temperatures from room temperature down to 20°K (−253°C or −423°F). Room temperature vulcanizing silicones, called RTVs, exhibit good cryogenic properties, and polyurethanes are very good. Figure 5.7 shows a comparison of strengths for some cryogenic and low-temperature adhesive types.

Cements and mortars tend to tolerate low temperatures quite well, even to cryogenic levels. However, they do not tend to tolerate temperature fluctuations very well, with most of them spalling or flaking at the surfaces and cracking internally due to non-uniform expansion and contraction.

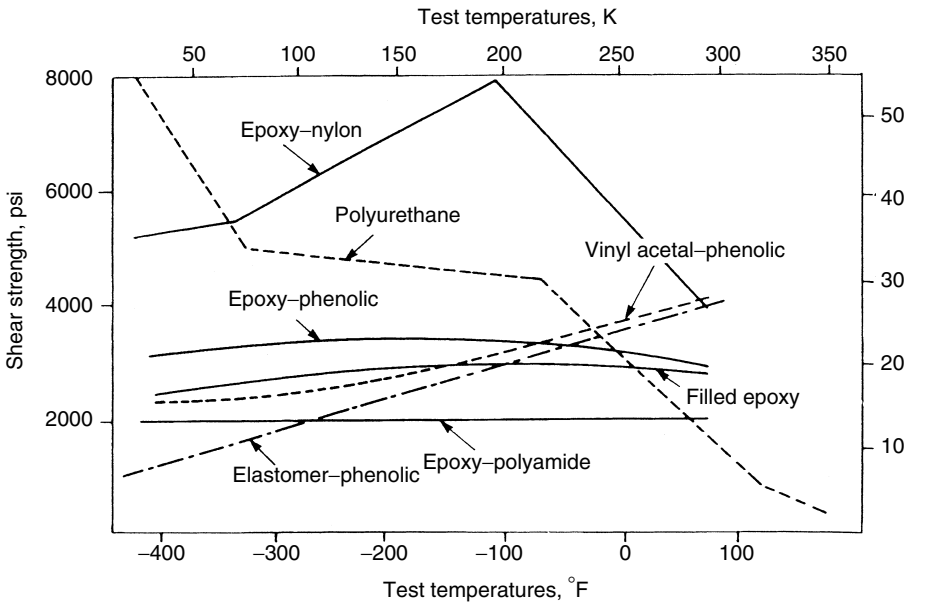

Figure 5.7 A comparison plot of the strengths of some cryogenic and low-temperature structural organic adhesives. (Reprinted from *Adhesives Technology Handbook*, A.H. Landrock, Fig. 9.1, page 245, Noyes Publications, Park Ridge, NJ, 1986, with permission.)

Humidity and Water Immersion

Moisture can affect the strength of an adhesive in two significant ways. First, it can cause "reversion." This is where the polymer loses its strength and rigidity and can liquefy in warm, humid air. Ester-based polyurethanes are an example of such polymers. Second, water can permeate the interface between an adhesive and an adherend, displacing the adhesive and causing loss of adhesion. This is called "water displacement" and is the more common mechanism of degradation. For either mechanism, degradation is usually worse in an aqueous-vapor environment than in liquid water because permeation is much more rapid. Stress on the adhesive accelerates the degradation even further. Moisture absorption also causes swelling of thermosetting polymers and adhesives, breaking cross-links between and bonds within molecular chains and generally leading to strength degradation.

Cement (e.g., Portland cement) tolerates humidity and water well.

Salt Water and Salt Spray

Salt water and, especially, salt spray are known to have deleterious effects on adhesive-bonded joints. Almost certainly, the mechanism is permeation and corrosion at the adhesive–adherend interface. In many adhesive-bonded samples exposed to salt water or salt spray, corrosive undercutting of the substrate adjacent to the interface with the adhesive has been observed, suggesting a "weak boundary layer" of some kind. One of the best-performing adhesive systems for this environment is the nitrile–phenolics.

Portland cements and most mortars do not tolerate salt water and salt spray as well as they tolerate plain water. However, they (as well as the concrete and other masonry structures they are used to create, most notably lighthouses) hold up quite well. The greater problem seems to be weathering.

Weathering

By far the most detrimental factors affecting adhesives used outdoors are heat and humidity, but temperature cycling, moisture cycling (i.e., wetting and drying), ultraviolet radiation from the sun, and oxidation also have minor degrading effects. In fact, it is the combined action of several of these factors during most outdoor applications that make "weathering" particularly severe.

When exposed to weather, structural adhesives typically lose strength rapidly during the first six months to one year. Then, after two to three years, the rate of degradation levels off at about 25–30% of the initial joint strength. In most cases, corrosion in the adherend or along the adhesive–adherend interface contributes to the degradation of the joint's strength. Other factors, such as the ultraviolet components of light, degrade thermosets by causing too much cross-linking, with attendant embrittling.

Two adhesive systems that tolerate weathering well are epoxy–phenolic and nitrile–phenolic film types.

Once again, as noted above, cements and mortars used in making concrete and other masonry structures can exhibit varying degrees of problems with weathering,

with cycling temperatures and periodic freezing when water manages to permeate joints being by far the most serious.

Chemicals and Solvents

Most organic adhesives tend to be susceptible to corrosive chemicals and solvents, particularly at elevated temperatures. Epoxy adhesives are generally more resistant to a wide variety of liquid environments than most other structural adhesives, and thermosetting adhesives are generally more resistant than thermoplastic adhesives. Without question, no one adhesive is optimum for all chemical environments, and selection of the right adhesive can be very difficult.

Portland cements and most mortars containing Portland cement are subject to degradation by inorganic acids and even some strong bases. Selective leaching of especially susceptible constituents leads to progressive degradation.

Vacuum

Vacuum, such as in outer space, degrades the performance of organic adhesives based on the degree of adhesive evaporation. Loss of low molecular weight constituents, such as plasticizers or diluents, can result in embrittling and/or porosity. Most structural adhesives have bases of predominantly high molecular weight polymers, so they tolerate vacuum well. Likewise, virtually all inorganic adhesives tolerate vacuum quite well.

Radiation

High-energy particulate and electromagnetic radiation, including neutron, electron, and gamma radiation, have effects similar to vacuum (i.e., they cause scission of the polymer molecular chains used in structural adhesives). This, in turn, causes weakening and embrittlement. The best-performing organic adhesives are the polysulfones, epoxies, polyimides, and polyurethanes. The inorganic types, including common cements and mortars, tend to do very well in radiation environments.

Biological Environments

Adhesives in bonded joints may or may not be attacked by biological organisms (e.g., fungi, mildew, bacteria, rodents, and insects), depending on how attractive they are to these organisms as a food source. Adhesives based on animal or plant materials (i.e., natural adhesives) are more likely to be affected than synthetic adhesives, although synthetic adhesives are not immune to attack. Even cement has problems with mildew and mold over time.

From the foregoing, it should be clear that the durability of an adhesive-bonded joint is critically dependent on the environment in which the joint is to perform, and many environmental factors degrade performance significantly—none more than time!

5.8 APPLICATIONS OF ADHESIVES, CEMENTS, AND MORTARS

The use of adhesives in both structural and nonstructural joining applications is growing dramatically. Clearly, cement and mortar use in masonry (especially the use of Portland cement in the production of concrete structures (many of which are massive) continues to grow in industrialized countries. And with the ever more rapid and widespread emergence of developing countries, the use of at least inorganic adhesives is also growing. Beyond this, as the science and engineering of polymeric materials improves, ever more numerous, diverse, and sophisticated applications of organic adhesives will also appear.

The amount of Portland cement produced in 2001, the latest year for which data was available, was staggering—1,650,000 metric tons for the world and 91,100 metric tons for the U.S. alone. Major applications of synthetic organic adhesives have occurred in the automotive, building construction, electrical and electronic, aerospace, marine, packaging, furniture, wood products, and other industries, and new and more sophisticated applications are appearing every day. Perhaps nowhere is the impact of structural adhesives more obvious than in the aerospace industry, which spearheaded the development of structural adhesives for joining metals that are now finding their way into the automobile industry. Let us look at just three indications of the importance of adhesives : the long-time workhorse Boeing 747 jumbo jet airliner, the growing use of adhesives in modern automobiles, and their technologically, economically, and environmentally important use in producing "engineered wood products."

The Boeing 747 jumbo jet uses $3,700\,m^2$ $(40,000\,ft^2)$ of structural adhesive film, almost 450 kg (1,000 lbs.) of polysulfone sealant, and 23 kg (50 lbs.) of silicone rubber sealant. Use of adhesives for structural strength, sealing, vibration damping, noise-deadening (to improve ride harshness), and thermal insulation has proliferated on modern automobiles, as shown in Figure 5.8, resulting in a typical total use of between 20 and 30 lbs. (about 10–15 kg) per vehicle. Structural adhesives are receiving serious consideration for the outright bond assembly (or, in some cases, weld bond or rivet bond assembly, as described in Chapter 10, Section 10.4) of aluminum-intensive automobiles. And, finally, adhesives (especially phenolics) are seeing increased use in the production of so-called "engineered wood products." Some maximize the utilization of the increasingly scarce resource of solid wood by allowing the use of material traditionally thrown away or burned, including the production of "press board" from sawdust, "flake board" from chips, and special bonded-up lumber for high-quality applications such as Anderson and Pella aluminum- or vinyl-clad windows. Some adhesives provide new performance capability, as in bonded, laminated beams that have greater load-carrying capability than much larger nailed buildups.

There will be substantial technological impact (despite small tonnage use) as specially formulated structural adhesives exhibiting intrinsic electrical conductivity challenge soldering in the electronics and microelectronics industries, and as adhesives are being increasingly used for joining living tissue and in fixing bionic implants.

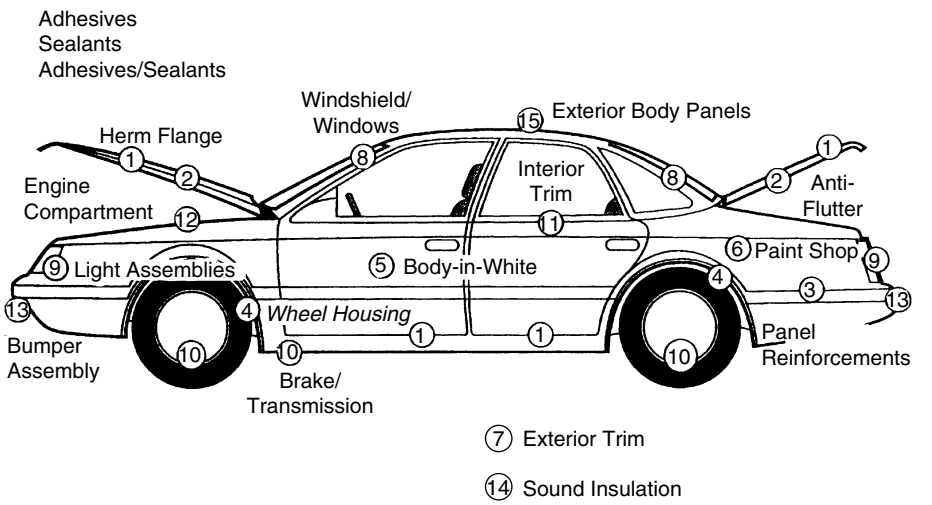

Figure 5.8 An illustration of the use of adhesives in a modern automobile, with the vehicle being shown in its "body-in-white" form. (Reprinted from *Adhesion and Adhesives*, A.V. Pocius, Fig. 1.3, page 6, Hanser Publishers, Munich, Germany, 1997, with permission.)

The adhesive-bonding process provides a much needed and valuable complement to the other principal joining processes of mechanical fastening, integral mechanical attachment, welding, brazing, and soldering.

SUMMARY

Adhesives are the key ingredients for accomplishing adhesive bonding (indisputably another extremely old joining process). Adhesives are usually mixtures of several constituents in carefully (but, especially in the past, mysteriously) formulated systems, which include an adhesive base or binder as the active chemical bonding agent; a diluent (for adjusting concentration or potency); a solvent (for adjusting consistency for ease of application); accelerants or retardants (to control working characteristics); hardeners (to cause thermosetting polymeric adhesives to cure by cross-linking); fillers (to impart special properties); and carriers or reinforcements (to support or strengthen the adhesive during application or in service, respectively). The diversity of adhesives and their use leads to several different schemes by which they can be logically classified, including by function (i.e., structural or nonstructural); as being natural or synthetic; as being organic or inorganic; by chemical composition; by physical form (e.g., liquids, pastes, films); by mode of application (e.g., sprayable, brushable, trowelable) or means of setting (for thermoplastic polymer types) or curing (for thermosetting polymer types); or by specific adherend (e.g., wood) or application (e.g., weatherable adhesives). Synthetic adhesives are preferred for structural applications and are, in turn, classified by the type of polymer constituting the base, including thermoplastic and

thermosetting types, elastomeric subtypes, and adhesive alloys of two or more of these. Important types of structural synthetic organic adhesives include epoxies, modified epoxies (usually alloys), acrylics and modified acrylics, cyanoacrylates (or "super glues"), anaerobics, urethanes, phenolics, silicones, hot-melt thermoplastics, and high-temperature thermosets. Another classification scheme based on chemical composition adapted by the SME considers chemically reactive adhesives, evaporation or diffusion adhesives, hot melts, delayed-tack adhesives, pressure-sensitive adhesives, and films and tapes.

The actual process of adhesive bonding involves the proper storage and preparation of the adhesive, proper preparation of the adherend or joint surfaces, proper application of the adhesive to the parts to be bonded and proper assembly of these parts, and proper setting or curing. Necessary equipment includes devices and procedures for controlling adhesive bond-line thickness; presses, autoclaves, or vacuum bagging systems for applying pressure; and ovens, autoclaves, baths, or heated platens for applying heat when needed for curing or drying. Achieving the desired and optimum bond performance requires pretesting of the properties of the adhesive and bonded joint in static tension, shear, peel, cleavage, and dynamic creep, fatigue, and impact using standardized methods such as those developed by the ASTM, as well as proper quality control during actual bonding using process-control specimens for destructive testing, and, at the very end of the process, using nondestructive inspection methods including visual, acoustic, ultrasonic, thermography, radiography, and other methods. Adhesive properties vary widely with adhesive type, composition, adherend, and, especially, environment. Environmental factors, such as temperature, moisture, chemicals, light, vacuum, radiation, and even biological agents, can significantly degrade the durability of a particular adhesive and bonded joint.

Throughout this chapter, the technologically and economically important behavior, compositions, properties, and environmental responses of cements and mortars used in masonry and, especially, concrete structures were described.

With proper adhesive selection and proper bonding procedures, the adhesive bonding process provides a much needed and valuable complement to the other principal joining processes of mechanical fastening, integral mechanical attachment, welding, brazing, and soldering.

QUESTIONS AND PROBLEMS

1. Adhesives are almost always actually systems comprised of two or more constituents that perform different but important roles. What are the six different constituents that can be found in adhesive systems? Briefly describe the role of each.
2. Referring to Question #1, which among the six different constituents frequently found in most synthetic organic adhesives are also found in a typical mortar used to erect masonry? Draw the parallels between those constituents found in mortars and those typically found in synthetic organic adhesives.

3. Some adhesives derive their active constituent from natural sources, creating what are known as "natural adhesives." What are the three broad categories of natural sources? Give three examples of specific materials from each source that can be used as the base for a natural adhesive.
4. Think about whether "Mother Nature" actually intended for some of those materials used as natural adhesives by human beings to also serve as adhesives in nature. Explain why they might actually have been intended to serve as adhesives, giving one example from each major source category.
5. What are "synthetic" adhesives in the most general sense of that term? Why are some naturally occurring or naturally derived adhesives often actually synthesized? Give a few examples.
6. Why do you suppose so many natural adhesives are based on polymeric materials, including proteins, as opposed to inorganic materials? (This is a tough one!)
7. What are the four major classes, or sub-classes, of synthetic polymeric adhesives? Differentiate among these four in the most general terms or characteristics.
8. Differentiate between a "structural" and a "nonstructural" adhesive in terms of intended performance. Now do the same based on the underlying chemistry of a well-known (and typical) example of each. (This is a tough one!)
9. Describe how thermosetting adhesives accomplish bonding. Give five examples of important thermosetting adhesives. Why is it important to the way these tend to be used that they are "thermosetting"? (This is a tough one!)
10. Describe how thermoplastic adhesives accomplish bonding. Give five examples of important thermoplastic adhesives. Why is it important to the way these tend to be used that they are "thermoplastic"? (This is a tough one!)
11. What is an "elastomeric" adhesive, and what is the basis of its exceptional elasticity? Why is it important to the way these tend to be used that they are "elastomeric"?
12. What is an "adhesive alloy"? Why are these especially important? Give five examples. From the standpoint of basic chemistry and atomic or molecular structure, how are "adhesive alloys" distinctly different from alloys found in metals and ceramics (i.e., inorganic materials)? (This is a tough one!)
13. Chemically reactive adhesives can consist of one or two components. Give three ways that a one-component adhesive can be activated. Give an example of an important adhesive activated by each mechanism. Explain why it is important to a representative example application using each mechanism that activation be possible this way. (This is a tough one!)
14. Nanotechnology has made it more practical to pre-mix two component systems that are activated by the occurrence of crack formation and propagation. They allow the practicality of "self-healing" materials. Look up and explain two ways in which this can be achieved. (This is a tough one!)
15. Describe how evaporation and diffusion adhesives operate to accomplish bonding. Give two important examples of each approach.
16. Differentiate between a "delayed-tack" and a "pressure-sensitive" adhesive. Give two examples of each, and give an important application for each type.

17. What is meant by the "physical form" of an adhesive? Why is this such an important consideration in manufacturing or construction? What are the popular physical forms, and what is an important example of each from your personal knowledge?
18. Give the specific means or mechanism by which each of the following adhesives develops adhesion: (a) cyanoacrylates; (b) anaerobics; (c) modified acrylics; (d) polyacrylates; (e) methylacrylates; (f) melamine–formaldehydes; (g) polybenzimidazole; and (h) styrene–butadiene copolymers.
19. Describe how common cement is produced from limestone and other mixed, crushed minerals. Explain the essential steps in the process of manufacture that allow the cement to operate as an adhesive.
20. What are some considerations regarding the storage of adhesives?
21. What are the major considerations in preparing joints for structural bonding?
22. What are the three major functions of equipment in bonding? Give three examples of each of the fundamentally different systems for each of the three purposes.
23. For what four purposes (not properties) are adhesives and adhesive-bonded joints destructively tested?
24. What are five major ways (as opposed to minor ways, or variations within a major way) that adhesive-bonded joints can be nondestructively examined? What are the strengths and limitations of each way?
25. The performance of an adhesive-bonded joint is greatly affected by the environment in which it is meant to function. What are the major environmental factors that can affect adhesive-bonded joint performance? Be thorough!

Bonus Problem:

After what you have learned about adhesive bonding (as a process for joining materials and structures) and adhesives (as chemical agents for obtaining adhesion) in Chapters 4 and 5, draw parallels between a typical synthetic, organic, thermosetting polymer-based adhesive being used to join an engineering ceramic (say, sapphire–alumina) restoration crown to a human's tooth and a typical Portland cement–lime mortar used to join pre-cast cement blocks. In your answer, consider each of the following:

1. The relative contribution of each of the four major mechanisms by which adhesives can develop adhesion.
2. The relative importance of the various parameters in Stefan's equation, i.e., viscosity, bond area, and bond-line thickness.
3. The relative effects of the way each cures to a hard, secure bond.
4. The relative way quality is assured in each, including the role of (a) destructive testing and (b) nondestructive inspection.

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Chapter 6

Welding as a Joining Process

6.1 INTRODUCTION TO THE PROCESS OF WELDING

Welding, as known by most people, might at first seem like a fairly new process. Intense blue-white electric arcs welding bridges, spark-spitting resistance robots welding automobiles, and thread-thin beams of laser light or electrons welding in outer space—all epitomize just how far we have come technologically when it comes to joining. But welding is actually quite old; it is ancient, in fact. While the great majority of welding processes were invented in fairly recent times, some, such as hammer or forge welding, have a very long history. Welding first evolved as an important technique for fabricating metals, as part of the copper- and then brass- and then iron-making processes,[1] as well as a principal means of making products from these metals by joining small pieces into larger objects. *Welding* involves bringing the surfaces of metals to be joined close enough together for atomic bonding to occur as the natural consequence of atoms seeking to create for themselves a stable electron configuration. In its broadest sense, welding includes any process that causes materials to join through the attractive action of interatomic or intermolecular forces, as opposed to purely macroscopic or even microscopic mechanical interlocking forces. Thus, welding (which will be addressed in this chapter), brazing (addressed in Chapter 7), soldering (addressed in Chapter 8), and even adhesive bonding (addressed in Chapter 4) can all be considered "welding" processes by the preceding definition.

Welding is critically important in modern manufacturing from a technological as well as an economic standpoint. It has been estimated that more than half of the gross national product of all industrialized countries comes about directly or indirectly from welding. Welding is used to join materials into parts and parts into assemblies and structures, or it is used to make the machines that make those materials or parts. It is also used fabricating machines mining natural resources or in agriculture to sow and harvest the plants we eat or use for clothing, shelter, or furniture. One only has to think about

[1] In fact, welding was an extremely important process in the evolution of the civilization of human beings in the Copper, then Bronze, and then Iron Ages, the latter of which began around the 8th century B.C., at least in Europe.

the pipelines used to transport natural gas and oil from the Bering Sea across Alaska and Canada to the continental United States or across the Ural Mountains from Russia to Western Europe, or the giant 100,000-ton supertankers that ply the oceans moving oil around the world, or the numerous offshore drilling platforms that tap new reserves of oil and natural gas, or liquid gas storage tanks, or the numerous pressure vessels and pipes in steam and power generation plants, or reaction or storage vessels in the chemical processing industries—the import and impact of welding becomes obvious. Figures 6.1 through 6.3 help give a sense of how welding impacts our lives every day in every way.

This chapter explores the process of joining by welding. First, the general mechanism by which a joint is formed between ideal as well as real materials is described, and the applicability of the process to metals, ceramics, glasses, and polymers, as well as their composites, is presented. Then, the relative advantages and disadvantages of welding versus other joining processes are described and discussed. Next, various schemes for classifying welding processes are presented, including pressure versus non-pressure processes, fusion versus non-fusion processes, classification by energy source, classification by liquid and/or solid reactions involved, and other schemes. Specific fusion and non-fusion welding processes are then described in some detail to give the reader a working knowledge of the many options available. These processes are compared in terms of the efficiency with which energy is transferred from the welding source to the joint to create the desired weld, and the particular advantages and limitations of each are highlighted. Finally, a brief discussion of weld-joint design is presented.

The subcategories of welding, namely brazing and soldering, are described in Chapters 7 and 8, respectively. The basics of the material science—physical metallurgy—that underlies the welding, brazing, and soldering processes are addressed in Chapter 9.

Figure 6.1 Typical large welded structures at a petrochemical plant. Note the bolted thick-section pipes, valves, and fittings at the left and right of the welded towers, as shown in a close-up in Figure 2.3. (Courtesy of Marathon Ashland Petroleum LLC, Findlay, OH, with permission.)

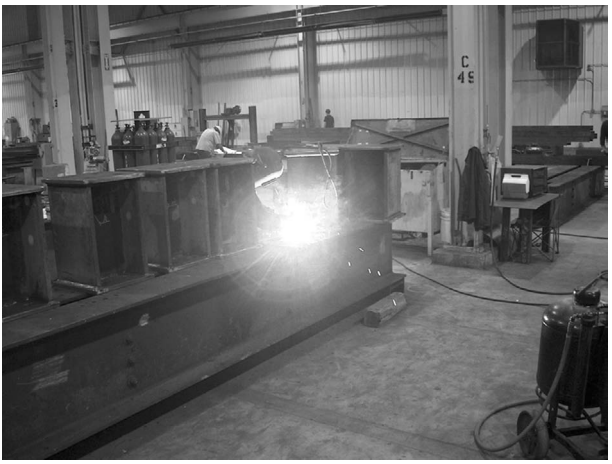

Figure 6.2 Large built-up beams and box sections are shown being welded in a fabrication shop for delivery to the site where a new bridge is to be constructed on site, also using electric arc welding. (Courtesy of the American Bridge Company, Coraopolis, PA, with permission.)

Figure 6.3 Robot-mounted welding heads are shown operating in a workcell as part of an automated production line for modern automobiles. Multiple robots are often used to speed assembly, with each performing a different set of specific welds over and over again. (Courtesy of KUKA Schweissanlagen GmbH, Augsburg, Germany, with permission.)

6.2 JOINING MATERIALS BY NATURAL PHYSICAL FORCES: WELDING

6.2.1 General Description

Welding is a process in which materials of the same basic type or class are joined together through the formation of primary (and, occasionally, secondary) atomic- or molecular-level bonds under the combined action of heat and pressure. These bonds are the natural consequence of bringing two similarly bonded materials together to allow interatomic or intermolecular attractive and repulsive forces to balance. The type of bonds formed across the joint is the same as the type of bonds found in the materials being joined.[2] Metals are joined in welding through the formation of metallic bonds. Glasses can be joined by welding, with primarily covalent or ionic bonds forming between the networks of the two glasses being joined, while ceramics can be joined by welding through the formation of ionic, covalent, or mixed bonds, depending on the particular ceramic(s) being joined. Thermoplastic polymers are joined in welding through the formation of some covalent bonds within molecular chains and substantial secondary bonds (e.g., by van der Waal's dipole bond formation, as well as substantial molecular entangling between long and complex molecular chains).

The key to all welding is atomic-level interdiffusion between the materials being joined, whether that diffusion occurs in the liquid, solid, or mixed state. Nothing contributes to joining better than actual interchange of atoms, ions, or molecules.

6.2.2 Creating a Weld with Atomic-Level Forces

Whenever two or more atoms are brought together from infinite separation, a force of electrostatic or Coulombic attraction arises between the induced dipoles that are created.[3] The attractive force increases with decreasing separation and, at the same time, a repulsive force arising as the negatively charged electron clouds of the atoms begin to sense one another also increases, but even more rapidly.[4] The net result is that the atoms reach a separation distance where the attractive and repulsive forces come into balance (i.e., at an equilibrium separation) and the atoms are bonded. At this

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[2] By this definition, dissimilar fundamental types of materials (e.g., metals and ceramics) cannot be welded to one another, because one material (the metal) is held together by metallic bonds and the other material (the ceramic) is held together by ionic, covalent, or mixed ionic–covalent bonds. Dissimilar types of materials can be joined by the subcategories of welding, namely brazing or soldering, or by adhesive bonding.

[3] As neutral atoms approach one another, the centers of charge distribution for the negative electrons (orbiting in their shells and subshells) of each atom shift away from one another and are no longer coincident with the centers of charge distribution for the positively charged nuclei. This is what leads to the creation of the induced dipoles, which are capable of attracting one another.

[4] The attractive force increases inversely to the approximate n power of the atomic separation, while the repulsive force increases to the approximate m power of the atomic separation, where $n < m$, and m is usually 11–12 and n is 2–6, depending on bond type.

point of zero net force, the net potential energy[5] (which is the sum of the attractive and repulsive potential energies) reaches a minimum, so the array is energetically stable. This is shown in the schematic plot of Figure 6.4. When the atoms are at their equilibrium spacing in a bonded aggregate, all of the atoms achieve stable electron configurations by sharing or by transferring electrons.[6] Obviously, what has just been described for neutral atoms can also occur for oppositely charged ions, leading to the formation of aggregates of ions called ceramic compounds or simply ceramics. For molecules having induced or permanent dipoles, this leads to the formation of polymers. The tendency for atoms to bond is the fundamental basis for welding, which has its origin for joining in these electromagnetically based physical forces. The challenge in welding, then, is to bring atoms to their equilibrium spacing to create a weld.

If two perfectly flat surfaces are brought to the equilibrium spacing for the particular atomic species involved in pairs across the interface, bond pairs form and the two pieces of material are welded together perfectly. In this case, there is no remnant of the prior physical interface and there is no disruption of the atomic-level structure of either material involved in the joint.[7] This ideal situation is shown in Figures 6.5a and 6.5b. The resulting *weld* has the strength expected from the binding energy (related to the depth of the well in the net potential energy curve in Figure 6.4), so the joint efficiency is 100%.

In reality, two materials never have perfectly smooth planar surfaces, so perfect matching up of atoms across an interface at equilibrium spacing never occurs, and a perfect joint or weld can never be formed simply by bringing the two materials together. Real materials have surfaces that are highly irregular. Peaks and valleys hundreds, thousands, and even tens of thousands of atoms high or deep lead to very few points of intimate contact where the equilibrium spacing can be reached. This is shown schematically in Figure 6.5c. Typically, only one out of every billion or so atoms along a real surface[8] can create a bond, so the joint strength is only about one-billionth of the theoretical strength that can be achieved. This situation is made even worse by the presence of oxide layers and adsorbed moisture layers usually found on real materials. As shown in Figure 6.5d, bonding, and thus welding, can only be achieved in such cases by removing or breaking these two layers and bringing the clean base material atoms within the equilibrium spacing[9] for the materials involved.

There are two ways of improving the situation, given that there are no practical ways of getting surfaces beyond a certain smoothness (i.e., to clean the surface of real

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[5] The potential energy and the forces of attraction and repulsion are related by the relationship $F = -dU/dx$, where F is the force of attraction or repulsion, U is the potential energy of attraction or repulsion, and x is the distance of separation. By convention, attraction is negative and repulsion is positive, based on how work must be done to change the separation. Hence the minus sign in the relationship.

[6] Electrons are shared in covalent and metallic bonds, while in ionic bonds there is an actual transfer of electrons from one atom to another in a bonded pair.

[7] This case applies to a crystalline or a non-crystalline (i.e., amorphous) material, with either the crystalline or the amorphous structure being preserved across the interface.

[8] The so-called "real surface" is actually fairly representative of a well-machined and polished material, with perhaps a 4 rms finish.

[9] Obviously, any other form of surface contamination (e.g., grease) only further exacerbates the situation.

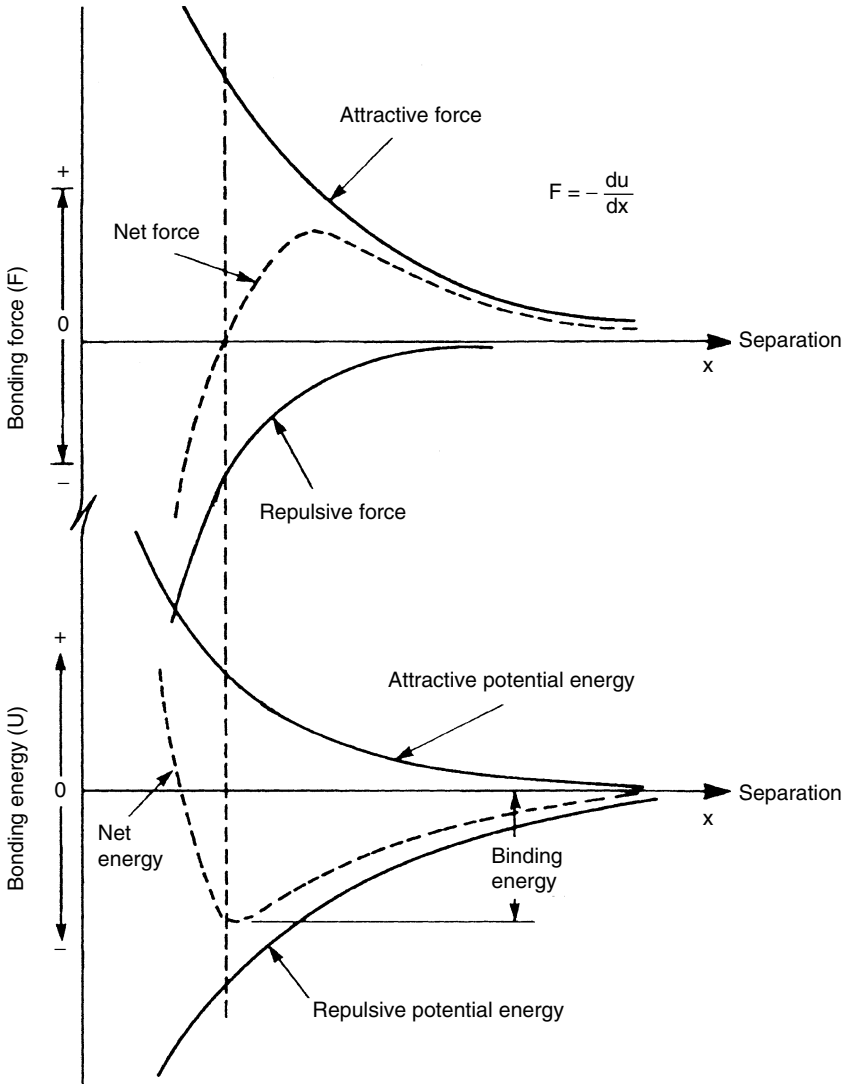

Figure 6.4 A schematic plot of the forces (a) and potential energies (b) involved in atomic bond formation as the underlying mechanism of welding. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.2, page 184, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

materials and bring most, if not all, of the atoms of those clean surfaces into intimate contact over large areas). The first is to apply heat; the second is to apply pressure. Heating helps welding to occur in several ways. In the solid state, heating helps by (1) driving off the adsorbed layers of gases or moisture; (2) breaking down the oxide or other tarnish layers through differential thermal expansion between them, as in ceram-

ics and the base metal (*or* occasionally by thermal decomposition); and (3) lowering the yield or flow strength of the base materials and allowing plastic deformation under pressure to bring more atoms into intimate contact across the interface. This is shown in Figure 6.5e. Alternatively, heating could help by causing melting of the substrate material to occur, allowing atoms to rearrange by fluid flow and come together to equilibrium spacing once solidification occurs, *or* by melting a similar filler material to provide extra atoms of the same or different but compatible types as the base material. This situation is shown in Figure 6.5f. Pressure helps welding occur by (1) disrupting the adsorbed layer of gases or moisture by deformation; (2) fracturing the brittle oxide or other ceramic tarnish layer to expose clean base material; and (3) plastically deforming the asperities to increase the number of atoms (and the area) in intimate contact (see Figure 6.5e). Figure 6.5g shows a near-perfect weld made in a non-ideal (i.e., real) material.

The relative amounts of heat and pressure necessary to create welds vary from one extreme to the other. Very high heat and no pressure (beyond what is needed to simply hold the two materials in contact at all!) can produce welds by relying on the

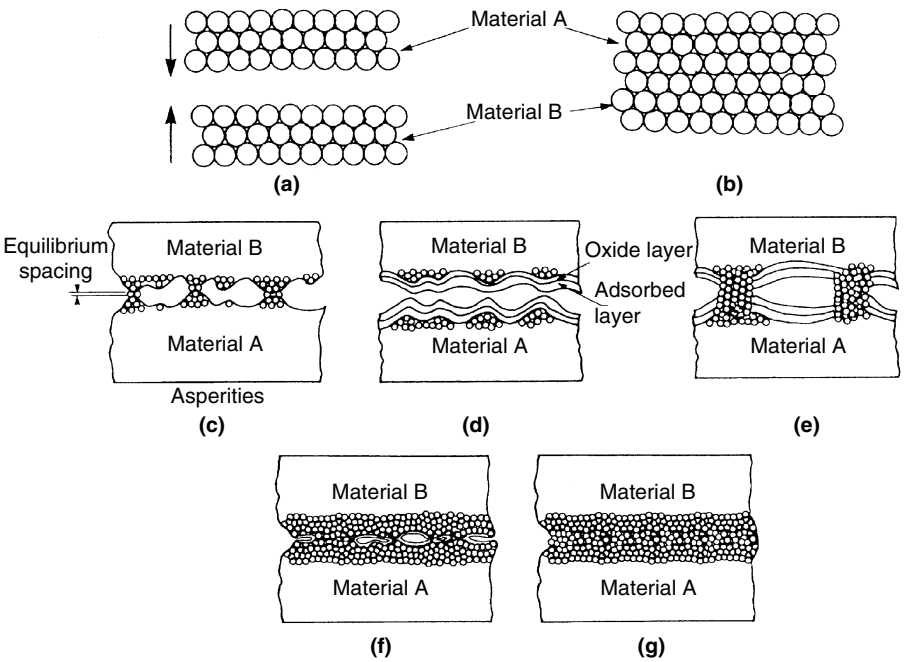

Figure 6.5 Schematic illustration of the formation of welds, as the result of two perfectly smooth and clean ''ideal'' materials versus two real materials. (a) The ideal surfaces before (a) and after (b) being brought into intimate contact (b). The real surfaces (c) that are not atomically smooth and (d) have adsorbed layers and oxides showing disruption of adsorbed layers (e) by heat or pressure and the progressive formation of a weld (f) and (g). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.3, page 185, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

high rate of diffusion in the solid state at elevated temperatures or in the liquid state produced by melting or fusion. Little or no heat with very high pressure can produce welds by forcing atoms together by plastic deformation, relying on diffusion in the solid state to cause subsequent atomic-level intermixing. Most welding processes involve a fair amount of heat and only enough pressure to hold the joint elements together during the welding process, but there are processes that predominantly employ pressure. In fact, welding processes are frequently classified by the amount of pressure or the amount of heat involved in producing the weld.[10] These are called *pressure* and *non-pressure* or *fusion* and *non-fusion* welding processes, respectively.

6.2.3 Welding Metals Versus Ceramics or Polymers

As was described in Subsection 6.2.1, materials can be welded if the atoms, ions, or molecules comprising those materials can be brought into intimate contact in sufficiently large numbers to produce enough bonds to lead to significant joint strength. Most people are familiar with the fact that metals can be welded, but fewer realize that ceramics, glasses, polymers, and even composites with these materials as matrices can also be joined by welding. The requirements are the same in each material; the only difference is the means for bringing atoms into contact and the type of atomic or molecular bonding that results.

In metals, metallic bonds are formed across the interface between them. In ceramics and glasses, ionic, covalent, or mixed ionic–covalent bonds are formed, depending on the specific nature of the ceramic or glass. In polymers, covalent bonds are formed, provided the polymers are suitably mixed by the action of the applied heat and/or pressure. Otherwise, secondary bonding, principally by van der Waal's dipoles, is the source of joint strength. In addition, significant intertwining or entangling of the long-chain molecules of many polymers (e.g., thermoplastics) gives rise to aggregation without the need for substantial bonding. In composites, welding actually occurs within the matrix materials, with metallic bonds forming between metal matrices, ionic or covalent or mixed bonds occurring between ceramic matrices, and secondary or covalent bonds and/or chain entangling occurring between polymer matrices.

While dissimilar metals can often be welded to one another (because even dissimilar metals bond metallically), it is impossible—in the pure sense—to weld dissimilar material types (e.g., metals or polymers) to one another. Likewise, dissimilar ceramics can often be welded to one another, provided both have similar bonding and are otherwise chemically compatible. For polymers, welding, in its true sense, is usually restricted to thermoplastic types. Thermosetting polymers are not normally welded.[11]

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[10] See Subsections 6.3.4 and 6.3.5 on pressure versus non-pressure and fusion versus non-fusion welding processes, respectively.

[11] In fact, for both thermosetting and thermoplastic polymers, some forms of adhesive bonding are very difficult to distinguish from welding, as bonds are formed across interfaces that are the same as those that exist within the polymer joint elements. The best example may be "solvent cementing," used with thermoplastics (see "Solvent cementing" in the Index).

The welding of various materials, by type, is discussed in detail in Chapter 11 for metals and alloys, Chapter 12 for ceramics and glasses, Chapter 13 for thermoplastic polymers, and Chapter 14 for various composites.

6.2.4 The Importance of Cleaning for Welding

As should be clear from the discussion of the impediment to welding between real versus ideal materials caused by contaminating surface layers, a critical step of any welding process is cleaning the surfaces to be joined and keeping them clean throughout the welding process, to allow the atoms of the materials being welded to come together to form bonds. Polymers and ceramics and glasses generally only need to have dirt or hydrocarbon contaminants (e.g., oil, grease, or wax) removed from their surfaces to be made clean enough for welding. Chemical and physical activation of the surfaces on even these materials certainly improves welding by solid-state, non-fusion approaches. This is because these materials, by their very nature, tend to be non-reactive. Metals, on the other hand, usually present additional cleaning requirements since they are generally reactive, especially when heated to near or above melting. Oxides, sulfides, and other surface scales must usually be removed and kept from reforming before the weld is formed.

For all materials, solvents can remove oil, grease, and particulate contamination. For some materials, notably metals, mechanical abrasion or chemical etching with acids or strong bases (or both) may be necessary to remove tenacious scales or oxides. Some welding processes use a chemical agent called a "flux" to clean and activate the surface of a material to promote bonding during the actual process of welding. Fluxes chemically reduce oxides and other surface contaminants on metals, producing a perfectly (i.e., atomically) clean surface. To work properly, these fluxes must remain on the metal surfaces being directly joined throughout the welding process to prevent recontamination by oxidation, for example. In the molten state, fluxes are especially active and aggressive cleaning agents, acting to scavenge undesirable oxidizing agents. Once they have done their job and have solidified, most welding fluxes are called "slag." The role of fluxes and slag in welding will be described with the description of specific welding processes (Sections 6.4 and 6.5).

Because they are usually reactive, metals must be protected or shielded from oxidation during welding, especially when heating is involved. *Shielding* can be provided by surrounding the pieces being welded with an inert atmosphere, or by otherwise excluding oxygen from the vicinity of the weld. Actual inert gases like argon or helium, non-reactive gases like dry nitrogen, or a vacuum can all be used with varying degrees of success, depending on the situation (e.g., especially the reactivity of the metals being welded!). Molten flux, and even reacted flux in the form of molten or solidified slag, can also serve as shielding, and does in some welding processes.

6.2.5 Advantages and Disadvantages of Welding

Welding offers several advantages over other joining processes, but it has some disadvantages too. The most significant advantage is undoubtedly that welding provides exceptional structural integrity—producing joints with very high efficiencies and, thus, weight advantages for the strength provided. Joint strengths can easily approach and even exceed the strength of the base material(s). Another advantage is the wide variety of approaches and processes that can be used and the wide variety of materials that can be welded. Almost all metals, virtually all glasses, all thermoplastics, and some ceramics, as well as the matrices of composites based on these materials, can be welded (within types) using a variety of pressure or non-pressure fusion and non-fusion processes, with or without auxiliary filler.

Other advantages of welding are that it can be done manually, semiautomatically, or completely automatically and can be made highly portable for implementation in the field for erection of structure on site or for maintenance or repair. In fact, it is not at all unusual (although it probably ought to be!) that welding is used to repair structures made from materials that were never intended to be, and were not originally, welded. Continuous welds provide fluid-tight joints, so welding is the process of choice for fabricating pressure vessels for gaseous materials and containers for liquid materials. For most applications, welding can be reasonable in cost, although highly critical welds, with stringent quality requirements or involving specialized applications (e.g., very thick sections), can be expensive.

The greatest disadvantage of welding is that it prevents disassembly. Often, however, this permanency is the reason for selection of this process in the first place. As mentioned, the process can be expensive if quality requirements are high or for special joining situations. The need for considerable operator skill and the occasional need for capital-intensive equipment (e.g., laser- or electron-beam welding systems) contribute to cost. From a materials standpoint, welding can degrade the properties of the base materials (particularly metals and ceramics) because of the effects of heat, especially for processes dependent on fusion. In metals, the cast microstructure that replaces what may have been a wrought microstructure can suffer from the adverse effects of solute segregation and other problems (including anisotropy) associated with dendritic growth. Unbalanced heat input or cooling also leads to shrinkage or thermally induced residual stresses or distortion.

All in all, welding is an extremely versatile process, offering exceptional joint integrity to the designer and flexibility to the process engineer. Table 6.1 summarizes the advantages and disadvantages or limitations of welding.

6.3 CLASSIFICATION SCHEMES FOR WELDING PROCESSES

6.3.1 The Need for Classification of Processes

Because welding is defined as a process in which materials of the same class are joined together through the formation of primary (or, occasionally, secondary) atomic

Table 6.1 Advantages and Disadvantages of Welding

Advantages	*Disadvantages*
• Joints are permanent, precluding accidental (or even intentional) disassembly and loosening • Wide variety of process embodiments • Applicability to many materials within a fundamental class • Allows manual or automated operation • Can be portable • Reasonable overall cost, usually • Provides leak tightness with continuous welds	• Prevents/precludes disassembly for any purpose • Heat of some welding (especially involving fusion) disrupts base material properties • Precludes joining between materials from different classes • Unbalanced heat input leads to distortion or residual stresses • Requires considerable operator skill • Can be expensive due to skilled labor rates or due to labor intensity for thick, long, or critical welds • Capital equipment can be expensive, especially for some automated processes

bonds under the combined action of heat and pressure, it should come as no surprise that an extremely large number and wide variety of physical embodiments exist, as well as several schemes by which these can be classified. Processes can be classified by whether heat or pressure predominates in bringing material interfaces together to allow bond formation, as well as by source of energy used in either case. Thus, fusion versus non-fusion and pressure versus non-pressure classifications using chemical, electrical, or mechanical sources of energy are most popular. Alternatively, in the most technical and international scheme, processes are classified by whether the reaction that leads to the formation of the weld occurs between a liquid and solid phase, entirely in the solid state, or between a vapor and a solid. Another less-important scheme considers whether a filler material is used or not, and, if so, whether that filler is the same or different from the base material(s). Finally, within one large group of welding processes using an electric arc as the heat source (i.e., arc-welding processes), processes can be subclassified by the nature of the electrode employed to produce the arc and, thus, the weld. In these processes, electrodes may or may not be intended to be consumed (i.e., consumable versus non-consumable electrode arc-welding processes). If electrodes are consumed, they may be used in continuous or discontinuous forms (i.e., continuous versus discontinuous consumable electrode arc-welding processes).

The following sections describe the most common schemes for classifying welding processes and list various processes within each scheme.

6.3.2 Classification of Welding Processes by Energy Source

No matter whether atoms are brought together at the interface between two materials to create a weld using thermal excitation (with or without actually causing melting) or cause plastic deformation, energy is always needed to make the process happen. Hence,

one very logical scheme for classifying welding processes is by the specific type of source employed to provide the energy needed to produce welds. Types of energy sources include (1) chemical sources, which generate heat from either (a) exothermic combustion of a fuel-gas using air or oxygen, or (b) an exothermic chemical reaction between a metal and a nonmetal or oxygen; (2) electrical sources, which generate heat from (a) an electric arc or plasma between an electrode and the weldment, (b) resistance (I^2R) heating of the work as part of an electrical circuit, (c) induction of an electric current (again, to give rise to I^2R, joule heating), or (d) excitation by microwave or radio-frequency radiation; (3) high-energy beam sources, which generate heat by converting the kinetic energy of the particles in the beam upon collision with the work; and (4) mechanical sources, which (a) generate heat by the conversion of work through friction, or (b) cause plastic deformation under pressure.

Table 6.2 lists welding processes by the primary energy source enabling weld formation.

Table 6.2 Welding Processes Listed by Energy Source

Mechanical	*Chemical*	*Electrical*
Cold Welding (CW)	Pressure Gas Welding (PGW)	Stud Arc Welding (SW)
Hot Pressure Welding (HPW)	Exothermic Pressure Welding	Magnetically Impelled Arc Butt (MIAB) Welding
Forge Welding (FOW)	Pressure Thermit Welding (PTW)	Resistance Spot Welding (RSW)
Roll Welding (ROW)	Forge Welding (FOW)	Resistance Seam Welding (RSEW)
Friction Welding (FRW)	Oxy-Fuel Gas Welding (OFW)	Projection Welding (PW)
Ultrasonic Welding (USW)	Exothermic Welding or Thermit Welding (TW)	Flash Welding (FW)
Friction Stir Welding (FSW)	Transient Liquid Phase Bonding (TLPB)	Upset Welding (UW)
Explosion Welding (EXW)		Percussion Welding (PEW)
Deformation Diffusion Welding (DFW)		Gas-Tungsten Arc Welding (GTAW)
Continuous Seam DFW (CSDFW)		Plasma Arc Welding (PAW)
Creep Isostatic Pressure Welding (CRISP)		Carbon Arc Welding (CAW)
		Atomic Hydrogen Welding (AHW)
		Gas-Metal Arc Welding (GMAW)
		Shielded-Metal Arc Welding (SMAW)
		Flux-Cored Arc Welding (FCAW)
		Submerged Arc Welding (SAW)
		Electrogas Welding (EGW)
		Electroslag Welding (ESW)

NOTE: Letter designations used are those recommended and standardized by the American Welding Society, Mami, FL.

6.3.3 Classification of Welding Processes by Phase Reaction

Given that welding actually comes about when continuity is obtained between atoms (in the case of polymers, between molecules) across an interface, a scheme has been proposed based on the fact that all processes involve at least one of three operations occurring at the interface, as articulated by Granjon (1991) and as paraphrased below:

a. Liquid–solid interface reactions or processes occur at the interface, in which bonds are obtained by epitaxial[12] solidification of a liquid phase in contact with a parent solid phase.
b. Solid–solid interface reactions or processes occur at the interface, in which bonds are obtained from solid-state contact between the parts of the assembly by some means involving pressure and diffusion.
c. Vapor–solid interface reactions or processes occur at the interface, in which material condenses from the vapor state onto a parent phase that remains solid to directly produce a bond (as in surface coating) or assist in the production of bonds (as in some forms of brazing).

The first two classes above can be further broken down as follows:

a.1. Liquid–solid interface reactions or processes involving melting and intermixing of the parent phase, with or without the participation of an added filler, to produce a weld upon solidification. (This mechanism underlies virtually all fusion-welding processes.)
a.2. Liquid–solid interface reactions or processes that occur without the melting of the parent phase but, instead, allow bond formation through the presence of a heterogeneous filler that is molten, leading to both a cleaning (fluxing) action and establishment of necessary continuity. (This mechanism underlies the subclasses of welding known as brazing and soldering, as well as a variant process known as braze welding.)
b.1. Solid–solid interface reactions or processes made possible by the prior formation or existence of a transient liquid or viscous phase that arises from the parent phase but is eliminated by any of several means (e.g., mechanical expulsion or interdiffusion) during a later stage of the welding process. (This is the mechanism that underlies pressure-dependent fusion processes and some non-fusion welding processes.)
b.2. Solid–solid interface reactions or processes that occur by the direct formation of bonds in the solid state, strictly as the result of having atoms forced into intimate contact. (This is the mechanism that underlies virtually all non-fusion welding processes.)

[12] Epitaxial solidification involves the addition of atoms from a liquid to the aggregate of atoms comprising the solid parent phase that remains in contact with that liquid.

This particular scheme is actually quite elegant in its simplicity and precision and has been adapted by the international welding community through the IIW (International Institute for Welding). It is shown in Table 6.3.

6.3.4 Pressure Versus Non-Pressure Welding Processes

Some welding processes depend on or are facilitated by the application of pressure[13] to bring the atoms of the materials being joined into intimate contact to allow bond formation across the interface. These processes are called *pressure welding* or *pressure bonding processes*.

The effect of pressure in accomplishing welding is multi-fold. First, it increases the number and area of direct contacts between mating substrates through the plastic deformation of the highest asperities, bringing lower-height asperities into contact. Second, it enhances diffusion of atoms across the interface—to eventually obliterate that interface—by increasing the temperature locally as the result of the mechanical work done in the deformation process and, to a lesser extent, through stress-enhanced diffusion. Obviously, both of these effects require that the materials being welded

Table 6.3 IIW Classification of Welding Processes by Phase Reactions

a.1	Liquid–solid interface reactions or processes with melting and intermixing of base metal(s)
	Oxy-fuel gas welding
	Electric arc welding (except MIAB welding)
	High-energy beam welding
	Resistance welding
	Some thermit welding
a.2	Liquid–solid interface reactions/processes without melting of base metal(s)
	Brazing
	Soldering
	Gas pressure welding
	Some resistance welding
	MIAB welding
b.1	Solid–solid interface reactions or processes enabled by transient liquid phase
	Friction welding
	Explosion welding
	Exothermic (e.g., SHS or CS) welding
	Flash and upset welding
b.2	Solid–solid interface reactions or processes occurring by direct bonding
	Cold welding
	Forge welding
	Diffusion welding

[13] The pressure being referred to here is much more than that needed to simply hold the pieces being welded together during the process of welding. Rather, it is high enough to cause plastic deformation on some reasonable scale along the interface between the materials being welded.

exhibit reasonable plastic behavior. Third, for some base materials that are covered with an oxide or other tarnish layer, pressure serves to either fracture and disrupt or, in some process embodiments, abrade that relatively brittle layer to reveal clean underlying material that can form bonds. Finally, pressure holds the joint elements together while the bond formation process occurs. Fixturing or holding pressures are normally only on the order of a few pounds per square inch or fractions of an MPa, while the pressures used to cause plastic deformation are normally thousands or tens of thousands of pounds per square inch (tens or hundreds of MPas).

There are very few cold pressure-welding processes, although cold welding is possible. Most pressure welding is done hot, using any of several different chemical, electrical, or mechanical heat sources to reduce the yield strength of the materials being welded to ease plastic deformation and to speed solid-state diffusion. In true pressure-welding processes, however, pressure is far more important than heat, and certainly melting or fusion is not necessary to produce the weld, although some melting may occur.

Non-pressure welding processes rely on heat only, with little or no pressure except that needed to hold the joint elements together during the process.

Various pressure-welding processes are listed in Table 6.4 by energy source, while pressure versus non-pressure processes are shown in an overall taxonomy of welding processes in Figure 6.6.

6.3.5 Fusion Versus Non-Fusion Welding Processes

Many more welding processes rely on heat than on pressure to accomplish joining by creating atomic bonding across the joint interface. This heat may cause melting or fusion or may serve only to soften the material in the solid state to facilitate plastic deformation. When significant melting is involved and necessary for welding to take place, however, the processes are called *fusion welding processes*. Bond formation is aided by the melting process, which provides a supply of highly mobile atoms throughout the interface (gaps), whether or not auxiliary filler material is used. If melting does not occur *or* is not principally responsible for causing welding (i.e., bond formation), the processes are called *non-fusion welding processes*. Heat must usually be involved, however.

Table 6.4 Pressure Welding Processes by Energy Source

	Energy Source	
Mechanical	*Chemical*	*Electrical*
Cold welding	Oxy-acetylene pressure welding	Spot welding
Friction welding	Exothermic pressure welding	Seam welding
Ultrasonic welding	Forge welding	Projection welding
Forge welding		Upset butt welding
Roll welding		Flash welding
Diffusion welding		Percussion welding
Explosion welding		Stud arc welding

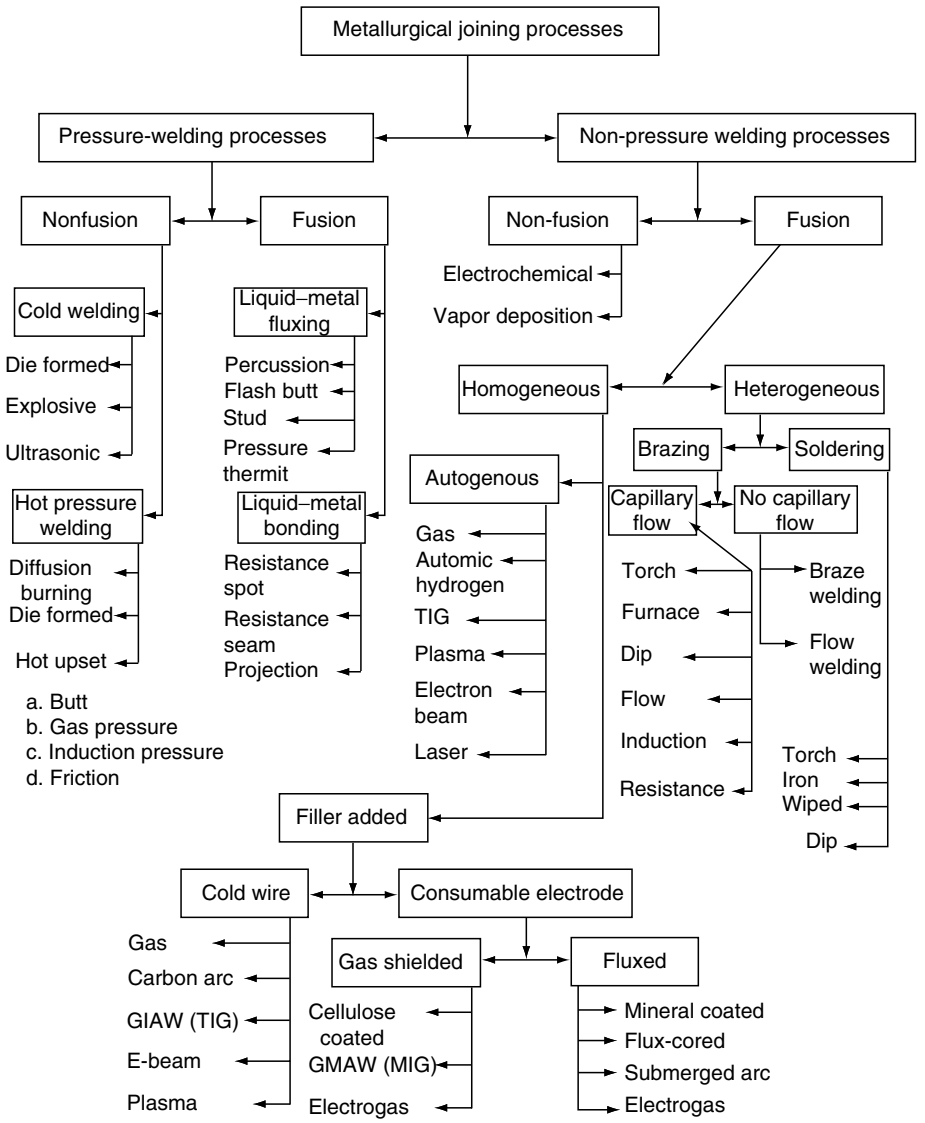


Figure 6.6 Schematic representation of the overall taxonomy of welding processes. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Fig. 6.4, page 191, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

In fusion welding, the source of heat can be chemical, electrical (arc or resistance), high-energy beams, or others such as microwave or induction.[14] Regardless of

[14] Some may consider the use mechanical means for generating heat, typically from friction, sufficient to cause some melting, but the small volume of melting that usually occurs is not necessary for bond formation, although it surely doesn't hurt.

the source of heat in fusion welding, however, fusion welds exhibit distinct microstructural regions or zones due to the various effects of the heat. While these zones will be described in more detail in Chapter 9, Subsection 9.2.4, it is worth listing them here. They are, from the centerline of the weld (i.e., the original centerline of the intended joint) where the temperature is highest, outward into the base material that remains at ambient temperature, (1) fusion zone (FZ); (2) partially melted zone (PMZ); and heat-affected zone (HAZ). The fusion zone can actually be subdivided into the fusion zone and bounding unmixed zone, while the heat-affected zone may actually be composed of subzones that correspond to different effects at different temperatures, but all in the solid state. These are all shown schematically in Figure 6.7.

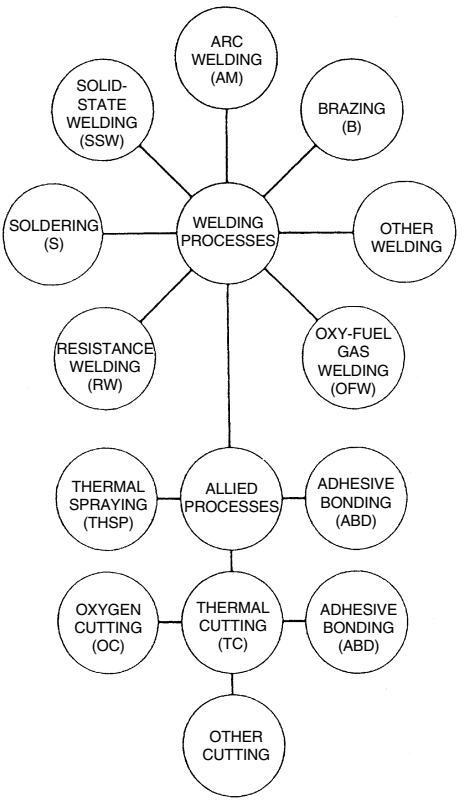
Table 6.5 lists fusion welding processes by energy source, while Figure 6.6 shows how fusion versus non-fusion processes fit within an overall taxonomy of welding and allied processes.

6.3.6 Autogenous Versus Homogeneous Versus Heterogeneous Welding

Within fusion welding, the various processes can be further subclassified by whether or not an auxiliary filler material is needed and, if so, whether that filler has the same or a different composition as the base material. When no filler is required or used, the process is called *autogenous*. Here, the source of atoms (or ions or molecules, for ceramics or polymers, respectively) required to help fill gaps at the interface due to microscopic asperities comes from the melted base materials themselves. For autogenous welding to produce structurally sound and attractive welds, the base materials making up the joint must be the same or highly compatible to allow mixing without problems, and the fit of the joint elements must be good (i.e., with little gaps) to preclude underfill of the finished joint.

If filler is required or used, the process is called *homogeneous* if the filler's composition is the same as the base material, and *heterogeneous* if it is different. For a process to be homogeneous, all components making up the joint (i.e., both base materials and any filler, in any form) must have the same composition. If the base materials making up the joint are of different compositions, the filler must be compatible with all of these, and the process is definitely heterogeneous.

Filler is often needed in fusion welding to make up volume in the joint—first, to compensate for the shrinkage that virtually always accompanies the solidification of a molten material and, second, to add material where there was none because of poor joint fitup. As mentioned earlier, filler also facilitates joining by bridging gaps at the joint faying surfaces by adding atoms. Since it is in the molten state, filler facilitates diffusion as well, which further tends to establish material continuity. For joints that are composed of two materials of the same type (e.g., both metals) but of different compositions (e.g., mild steel and gray cast iron), the filler often is selected to make the two material compositions compatible (e.g., pure Ni, Fe-55Ni, or austenitic stainless steel). Fillers are available in several different forms, including electrodes that are consumed by the heat of the arc to provide filler, wires that are either preplaced in



(a)

Group	*Welding Process*	*Letter Designation*
Arc welding	Carbon arc	CAW
	Electrogas	EGW
	Flux-colored arc	FCAW
	Gas metal arc	GMAW
	Gas tungsten arc	GTAW
	Plasma arc	PAW
	Shielded metal arc	SMAW
	Stud arc	SW
	Submerged arc	SAW
Brazing	Diffusion brazing	DFB
	Dip brazing	DB
	Furnace brazing	IB
	Induction brazing	IRB
	Resistance brazing	RB
	Torch brazing	TB
Oxy-fuel gas welding	Oxyacetylene welding	OAW
	Oxyhydrogen welding	OHW
	Air acetylene	
	Pressure gas welding	PGW
Resistance welding	Flash welding	FW
	Projection welding	DFW
	Resistance seam welding	RSEW
	Resistance spot welding	RSW
	Upset welding	UW
Soild-state welding	Cold welding	CW
	Diffusion welding	DFW
	Explosion welding	EXW
	Forge welding	FOW
	Friction welding	FRW
	Hot pressure welding	HPW
	Roll welding	ROW
	Ultrasonic welding	USW
Soldering	Dip soldering	DS
	Furnace soldering	FS
	Induction soldering	IS
	Infrared soldering	IRS
	Iron soldering	INS
	Resistance soldering	RS
	Torch soldering	TS
	Wave soldering	WS
Other welding processes	Electron beam	EBW
	Electroslag	ESW
	Flow	FLOW
	Induction	IW
	Laser beam	LBW
	Percussion	PEW
	Thermit	TW

(b)

Figure 6.7 The AWS classification of welding and allied processes in a master chart (a), along with a list of processes with their AWS letter designations (b). (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Fig. 6.6, page 197, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA and the American Welding Society, Miami, FL.)

the joint or fed into the joint during welding, shims that are preplaced in the joint, or powders that are added to the joint during welding.

Autogenous, homogeneous, and heterogeneous processes are shown in the taxonomy in Figure 6.6.

Table 6.5 Fusion Welding Processes by Energy Source

Energy Source		
Chemical	*Electrical*	*Miscellaneous*
Oxy-fuel gas welding[1]	Gas-tungsten arc welding[5,6]	Laser beam welding[8]
Exothermic (thermit) welding[2]	Carbon arc welding[5,6]	Electron beam welding[8]
Torch brazing[3]	Atomic hydrogen welding[5,6]	Furnace brazing[4]
Braze welding[4]	Plasma arc welding[5,6]	Dip brazing[4]
	Shielded metal arc welding[7]	
	Flux-cored arc welding[7]	
	Gas-metal arc welding[7]	
	Submerged arc welding[7]	
	Electrogas welding[7]	
	Electroslag welding[7]	
	Induction brazing[4]	
	Resistance brazing[4]	

[1] Normally performed autogenously, but can use homogeneous or heterogeneous filler
[2] Normally performed with homogeneous filler, but could operate with heterogeneous filler
[3] Normally performed with heterogeneous filler
[4] Always performed with heterogeneous filler
[5] Employs a nonconsumable electrode of homogeneous or heterogeneous filler
[6] Can be performed autogenously
[7] Employs a consumable electrode of homogeneous or heterogeneous filler
[8] Usually performed autogenously, but can use a filler

6.3.7 Nonconsumable Versus Consumable Electrode Arc Welding Processes

In electric arc fusion welding processes, the electrode used to strike the arc with the workpiece can serve only as the means for carrying current to the arc and, thereby, heat the substrates, or it may be consumed in the arc to contribute filler as well as heat to the weld. In the first case, the process is referred to as a *nonconsumable* or *permanent electrode welding process*, while in the second case, the process is referred to as a *consumable electrode welding process*. Figure 6.6 shows the relative position of nonconsumable and consumable electrode welding processes in the taxonomy of all welding and allied processes.

6.3.8 Continuous Versus Discontinuous Consumable Electrode Arc Welding Processes

Consumable electrodes used in electric arc fusion welding processes can be *continuous* in form, consisting of long wires fed into the arc by a mechanical device, or *discontinuous*, consisting of discrete lengths of rods or wires, usually fed manually into the arc. This distinction is of significance primarily for the difference in productivity that can be expected and obtained between the two broad types. Continuous consumable

electrode processes are far easier to automate and, whether operated manually or automated, result in less downtime to change electrodes and, thus, in higher deposition rates. Figure 6.6 indicates whether a particular electric arc welding process uses a continuous or discontinuous consumable electrode.

6.3.9 The American Welding Society's Classification of Welding and Allied Processes

The American Welding Society (AWS) has developed its own classification of welding processes, including brazing, soldering, and other allied processes. This classification uses many of the classification schemes described in the preceding subsections. More than 40 welding processes are recognized, as well as nearly a dozen each of brazing and soldering processes. The AWS also includes some processes allied to welding by the fact that they, too, rely on heat, often from the same sources as used for welding, including thermal cutting, heat straightening, etc. The AWS Classification of Welding and Allied Processes is shown in Figure 6.8.

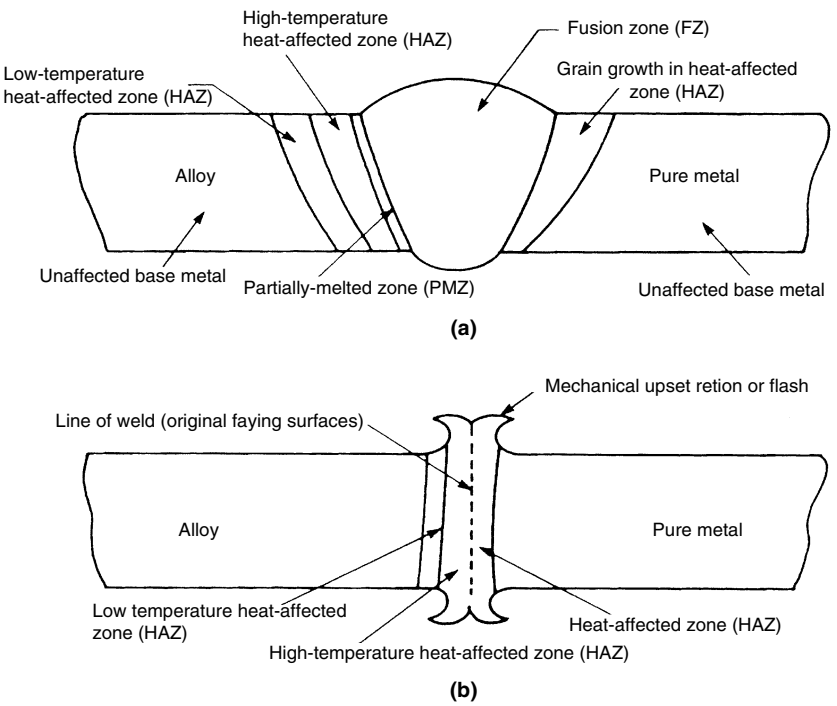


Figure 6.8 Schematic illustration of the various microstructural zones in typical, hypothetical (a) fusion and (b) non-fusion welds. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.5, page 193, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

6.4 FUSION WELDING PROCESSES

6.4.1 General Description of Fusion Welding Processes

In fusion welding, the edges or surfaces of pieces to be joined are heated to above their melting point[15] and the atoms (or molecules, in the case of polymers or glasses) in the two materials are brought together in the liquid state to create large numbers of bonds after solidification. Sometimes additional filler material must also be melted and added to completely fill the joint gap. Fusion welding processes include all of the processes in which the melting or fusion of portions of the substrates, with or without added filler, plays a significant role in the formation of bonds producing a joint.[16] As shown in Figure 6.7, fusion welds contain a distinct fusion zone, surrounded by partially melted, heat affected, and unaffected base metal as temperature decreases from the point of maximum heating to the unheated portion of the structure or weldment.

The following sections describe some of the main fusion welding processes, in order to highlight the principal characteristics of such processes rather than attempt to be complete. The processes to be described include (1) gas welding using a combustible fuel as the source of heat; (2) arc welding using an electric arc from either a non-consumable electrode or a consumable electrode as the source of heat; (3) high-energy beam welding using the conversion of kinetic energy of fast-moving particles in an intense radiant beam as the source of heat; and (4) resistance welding using I^2R losses in the workpiece as the source of heat. A more comprehensive overview of fusion processes is presented by Messler (1999) and a much more detailed description is provided by the American Welding Society (1990).

6.4.2 Gas Welding

Gas welding includes any welding process in which the source of heat for welding is the exothermic chemical combustion of a fuel gas with oxygen. Natural gas, MAPP gas, propane, butane, and other hydrocarbon gases (or even hydrogen) can be used, although acetylene gas is the most widely used fuel in the process of oxyacetylene welding because of its high flame temperature or source energy.

Oxyacetylene welding (OAW[17]) derives the heat needed to cause melting of the substrates and filler for a weld from two stages of combustion. They are first stage,

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[15] The term "melting point" actually refers to the discrete temperature at which a pure crystalline material transforms from a solid to a liquid upon heating. For an impure crystalline material, this transformation takes place over a range that begins at the solidus temperature and is complete at the liquidus temperature. For such materials, reference to "melting point" should indicate that the solidus temperature has been exceeded, for at this point a crystalline material's cohesive strength drops to zero.

[16] There are some processes in which some melting or fusion occurs but the principal mechanism for bringing atoms together to form bonds is plastic deformation under pressure. An example is flash welding (see Subsection 6.4.5).

[17] The American Welding Society (AWS) has developed an internationally accepted standard abbreviation for welding processes, and that nomenclature will be used here.

partial primary combustion of the acetylene fuel gas from a pressurized gas cylinder by pure oxygen from a pressurized gas cylinder to form carbon monoxide and hydrogen, and the second stage is complete secondary combustion of the carbon monoxide to carbon dioxide and the hydrogen to water vapor by the oxygen contained in the air surrounding the weld. The reactions are:

$$2C_2H_2(\text{cylinder}) + O_2(\text{cylinder}) = 4CO(\text{gas}) + 2H_2(\text{gas}) \tag{6.1}$$

then

$$4CO(\text{gas}) + 2O_2(\text{air}) = 4CO_2(\text{gas}) \tag{6.2}$$

and

$$2H_2(\text{gas}) + O_2(\text{gas}) = 2H_2O(\text{vapor}) \tag{6.3}$$

Both reactions give off heat (i.e., are exothermic), with the first accounting for one-third of the total heat generated by burning acetylene completely in oxygen., The second reaction gives off two-thirds of this heat. Of equal or greater significance, these two ''linked'' reactions occur in two distinct regions of the gas combustion flame, as shown in Figure 6.9. Primary combustion occurs in an ''inner cone,'' while secondary combustion occurs as the incompletely combusted products of this reaction move outward to react with oxygen in the air in an ''outer flame'' (Figure 6.9a). The more intense heating occurs at the tip of the ''inner cone,'' with the outer flame providing a non-oxidizing shielding around the hot and highly reactive molten weld pool and surrounding heated metal.

The exact chemical nature (reactivity) of the flame in gas welding processes, such as oxyacetylene, can be adjusted to be chemically neutral, chemically reducing, or chemically oxidizing by adjusting the relative amounts (actually, volume flow rates) of acetylene and oxygen from the pressurized gas cylinders. The neutral flame occurs when the molar ratio of fuel gas to oxygen is 2:1. Excess fuel gas leads to a reducing flame, while excess oxygen leads to an oxidizing flame. Adjustment is made simple by the appearance of a blue ''acetylene feather'' (as shown in Figure 6.9b) that appears at the edge of the inner cone when the neutral flame just begins to become reducing. Increasing the acetylene further increases the reducing character, while increasing the oxygen (to make the flame more white than blue) increases the oxidizing character. An oxy-fuel gas flame is lit by turning on the fuel gas only, lighting it (to produce a sooty yellow flame), and then turning on the oxygen to get the desired flame character. To extinguish the flame, the fuel gas is turned off first.

While the neutral flame is best for most welding, a reducing flame is good for removing light oxide tarnish from metals like aluminum or magnesium and preventing oxidation during welding, such as in the decarburization of steels. An oxidizing flame causes the metal being welded to form an oxide layer that can help prevent outgassing of high vapor pressure components such as zinc from brass alloys.

The oxyacetylene gas welding process is simple, is highly portable, and requires inexpensive equipment, consisting of cylinders of pressurized gas, gas regulators for controlling pressure and flow rate, a torch for mixing the gases for combustion, and

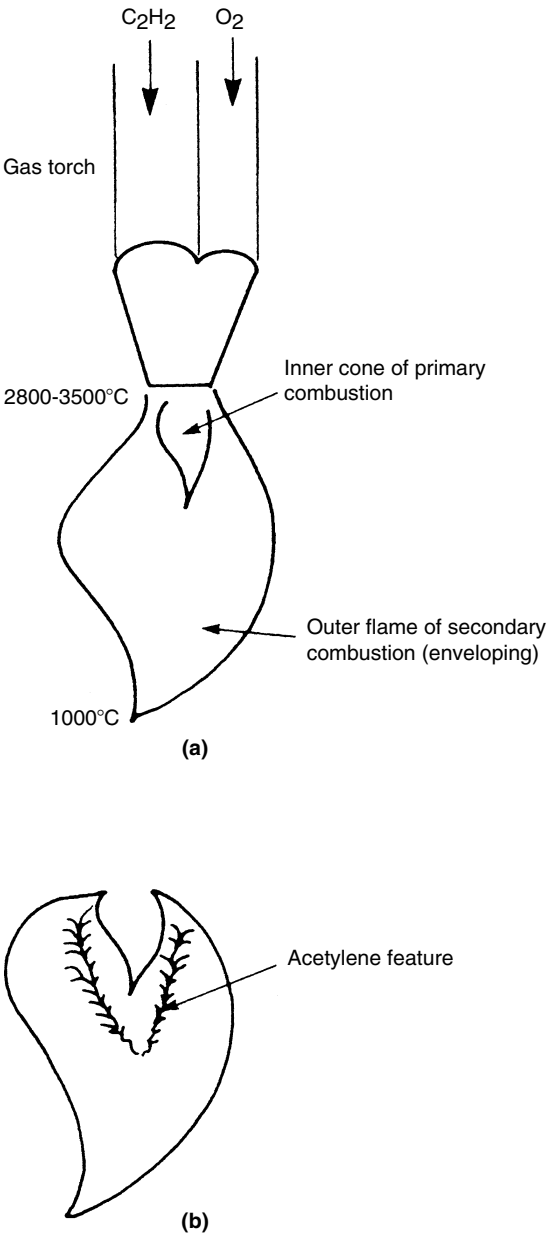

Figure 6.9 Schematic of a typical oxy-fuel gas flame used in welding and cutting; here, showing an oxyacetylene flame adjusted to be neutral (a) and reducing (b). The primary and secondary regions of combustion are shown in (a), while the acetylene ''feather'' characteristic of a reducing flame is shown in (b). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.7, page 199, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

hoses for delivering the gases from the cylinders to the torch. A typical torch is shown schematically in Figure 6.10. The process suffers from limited heating capacity (or heated volume) and intensity (which is manifested as higher attainable peak temperature). The total heat input per linear length[18] of weld can be high, leading to distortion. Also, the nature of the process limits the amount of protective shielding provided to the weld, so welding of more reactive metals (e.g., titanium) is generally impossible. To offset this particular shortcoming, OAW may employ a fluxing agent (such as borax) to provide additional protection to the weld to prevent oxidation during welding and/

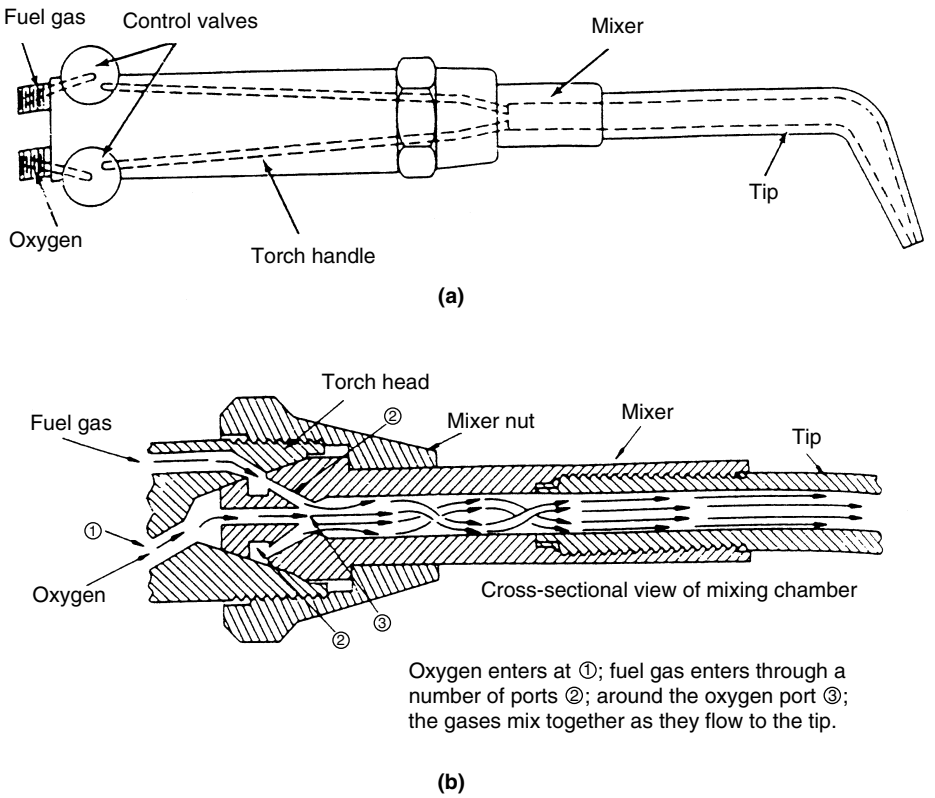

Figure 6.10 Schematic illustration showing (a) the basic elements of an oxy-fuel gas torch and (b) details of the gas mixer for a positive-pressure type torch. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.8, page 200, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA, and the American Welding Society, Miami, FL.)

[18] The heat input per linear length of weld is an important measure of how much thermal distortion or metallurgical transformation (i.e., heat-affected zone) can be expected. The analogy is running one's finger through the flame of a candle. Moving quickly causes no burning sensation, as heat input per unit length is low. Moving slowly causes a burn. Likewise, welding at high speeds results in a lower heat input per unit length of weld than welding slowly.

or clean the workpiece to promote wetting and flow by any filler metal.[19] Proper gas welding requires considerable operator skill and is usually performed manually.

Oxy-fuel processes can be used for cutting, gouging (i.e., grooving), or piercing (i.e., producing holes) in the allied process of oxy-fuel gas cutting, as well as for welding. In cutting, the process involves melting the base material and blowing the molten material away with a jet of compressed air or oxygen. Torch designs, for the most part, are the same.

6.4.3 Arc Welding

Fusion welding processes that use an electric arc as a heat source are called *arc welding processes.* The arc consists of thermally emitted electrons and positive ions from both the welding electrode and the workpiece and the intervening atmosphere. These electrons and positive ions are accelerated by the potential field (i.e., voltage) between the source (i.e., one electrode) and the workpiece (i.e., the oppositely charged electrode). They produce heat when they convert their kinetic energy by collision with the oppositely charged element. Arc welding includes a large and diverse group of process embodiments or processes, as shown in Table 6.5.

The arc in arc welding is created between an electrode and a workpiece or a weldment at different polarities. The electrode can be intended to be permanent, serving solely as a source of energy from electrons and positive ions, or consumed, in which case it serves as both a source of energy for welding and filler to assist in making the weld. If the electrode is intended to be permanent, then the processes are called "nonconsumable electrode arc welding processes." If the electrode is intended to be consumed, then the processes are called "consumable electrode arc welding processes." For nonconsumable electrode processes, if filler metal is required, it must be added from a supplemental source (e.g., filler wire). Nonconsumable electrodes are usually composed of tungsten or carbon (in the form of graphite) because of their very high melting temperatures, but they must be protected from oxidation by an inert shielding gas. Consumable electrodes are composed of the metal or alloy needed in the filler and come in the form of rods or sticks (i.e., as discontinuous electrodes) or as wires (i.e., as continuous electrodes).

Whether the arc welding process uses a nonconsumable or a consumable electrode, shielding must be provided to the weld by a chemically inert (or at least non-oxidizing) gas generated by decomposing the coating on or flux core in a consumable electrode or from an external inert gas source (e.g., pressurized gas cylinder). This shielding is to prevent oxidation of the highly reactive molten weld metal, and also to stabilize the arc.

Several of the more common arc welding processes are described in the following paragraphs in an effort to provide the reader with an understanding of key characteristics rather than a comprehensive knowledge. Nonconsumable electrode processes are described first, then consumable electrode processes.

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[19] "Wetting" is the phenomenon of a liquid attaching to a solid at a low angle of contact, tending to form a thin film rather than beads. The better the wetting during welding, the better the molten metal spreads over and adheres to the unmelted base metal(s).

Nonconsumable Electrode Arc Welding Processes

Six predominant arc welding processes use nonconsumable electrodes: (1) gas-tungsten arc welding (GTAW); (2) plasma arc welding (PAW); (3) carbon arc welding (CAW); (4) stud arc welding; (5) atomic hydrogen welding (AHW); and (6) magnetically impelled arc butt (MIAB) welding. Of these, the carbon arc and atomic hydrogen processes are rarely used any more. The magnetically impelled arc butt welding process is practiced little outside of Eastern Europe and the former Soviet Union (although it has potential). And the stud arc welding process has a highly specialized role for attaching threaded or unthreaded studs to structures (especially steel structures) using the heat generated by an arc between the stud and the workpiece and applying a pressure. The two predominant processes, gas-tungsten arc and plasma arc welding, will be described in some detail.

Gas-Tungsten Arc Welding

Gas-tungsten arc welding (GTAW) uses a permanent, nonconsumable tungsten electrode to create an arc to the workpiece. This electrode is shielded by an inert gas such as argon or helium to prevent electrode degradation by oxidation, hence its older, common names, "tungsten inert gas (TIG)" and "heli-arc" welding. As shown in Figure 6.11, current from a power supply is passed to the tungsten electrode in a torch (shown in Figure 6.12) through a contact tube. The tube is usually water-cooled copper to prevent overheating. The gas-tungsten arc welding process can be performed with or without filler (i.e., autogenously). When no filler is used, joints must be thin and tight-fitting square butts (described in Section 6.6).

The GTAW process can be operated in several different current modes, including direct current (DC) with the electrode negative (EN) or positive (EP), or alternating current (AC). These different current modes result in distinctly different arc and weld characteristics. (This applies to several other arc welding processes as well, including shielded-metal arc welding (SMAW), gas-metal arc welding (GMAW), and flux-cored arc welding (FCAW)).

When the workpiece or weldment is connected to the positive terminal of a direct-current power supply, the operating mode is referred to as "direct current straight polarity" (DCSP) or "direct current electrode negative" (DC− or DCEN). When the workpiece is connected to the negative terminal of a direct power supply, the operating mode is referred to as "direct current reverse polarity" (DCRP) or "direct current electrode positive" (DC+ or DCEP). In DCSP, electrons are emitted from the tungsten electrode and are accelerated to very high velocities and kinetic energy while traveling through the arc. These high-energy electrons collide with the workpiece, give up their kinetic energy, and generate considerable heat in the work. Consequently, DCSP results in deep-penetrating, narrow welds but with higher workpiece heat input. About two-thirds of the heat available from the arc (after losses from various sources) enters the work. High heat input to the workpiece may or may not be desirable, depending on such factors as required weld penetration (dependent on joint thickness), required weld width (dependent on joint fitup), workpiece mass (dependent on part size

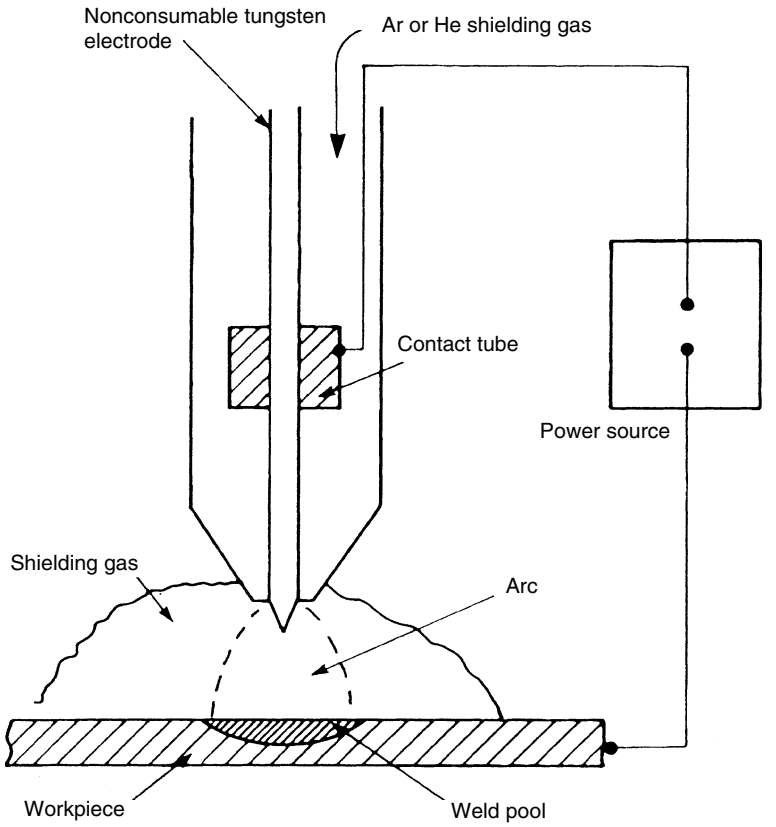

Figure 6.11 Schematic illustration of the electrical hookup of the GTAW process. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.9, page 202, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

and section thickness), workpiece thermal conductivity (high conductivity needing higher heat input), susceptibility to heat-induced defects, and concern for distortion or residual stresses (with high heat input being problematic in both regards). In DCRP, on the other hand, the heating effect of the much higher kinetic energy electrons is on the tungsten electrode rather than on the workpiece. Hence, larger, water-cooled electrode holders are required, shallow welds are produced, and workpiece heat input can be kept low. This operating mode is good for welding thin sections or heat-sensitive metals and alloys. This mode also results in a scrubbing action on the workpiece by the large positive ions that strike its surface, removing oxide and cleaning the surface. This mode is preferred for welding metals and alloys that oxidize easily, such as aluminum and magnesium.

The DCSP mode is much more common than the DCRP for nonconsumable electrode processes like GTAW and PAW, while the DCRP mode is much more common for consumable electrode processes like GMAW, SMAW, and FCAW,

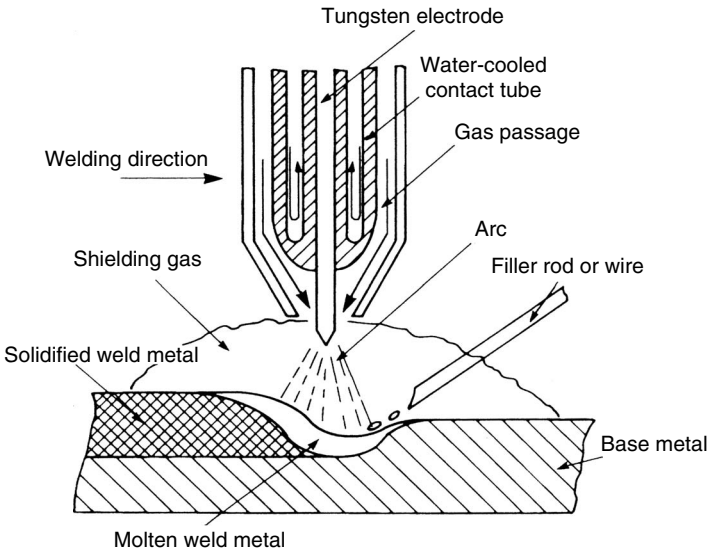

Figure 6.12 Schematic illustration of a gas–tungsten arc welding torch, weld, and filler wire. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.10, page 202, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science Burlington, MA.)

since the extra heat appearing in the electrode facilitates its melting to become needed filler. There is, however, a third mode, using alternating current, or AC. This mode tends to give some of the characteristics of both of the DC modes during the corresponding half-cycles, but with some bias toward the straight polarity half-cycle. During this half-cycle, the current tends to be higher because of the extra emission of electrons from the smaller, sharper, hotter electrode versus a large, blunter, cooler workpiece. In the AC mode, reasonably good penetration is obtained, along with some oxide cleaning action. Figure 6.13 schematically summarizes the characteristics of the various current or operating modes of the GTAW process.

The electron emission of tungsten electrodes is occasionally enhanced by adding 1–2% of thorium oxide or cerium oxide to the tungsten. This addition improves the current carrying capacity of the electrode, results in less chance of contamination of the weld by expulsion of tungsten as a result of localized melting of the electrode and allows easier arc initiation. While both argon and helium are used for shielding with the GTAW process, argon offers better shielding because it is heavier and stays on the work. Arc initiation is also easier because the required ionization potential is lower than for helium. The advantage of helium is a hotter arc.

In summary, the GTAW process is good for welding thin sections because of its inherently low heat input. It offers better control of weld filler dilution by the substrate than many other processes (again because of low heat input), and it is a very clean process. Its greatest limitations are its limited penetration capability (typically about 3–4 mm ($\frac{1}{8}$ - $\frac{3}{16}$ in.) and slow deposition rate (typically less than 1 kg (2 lb.) per hour).

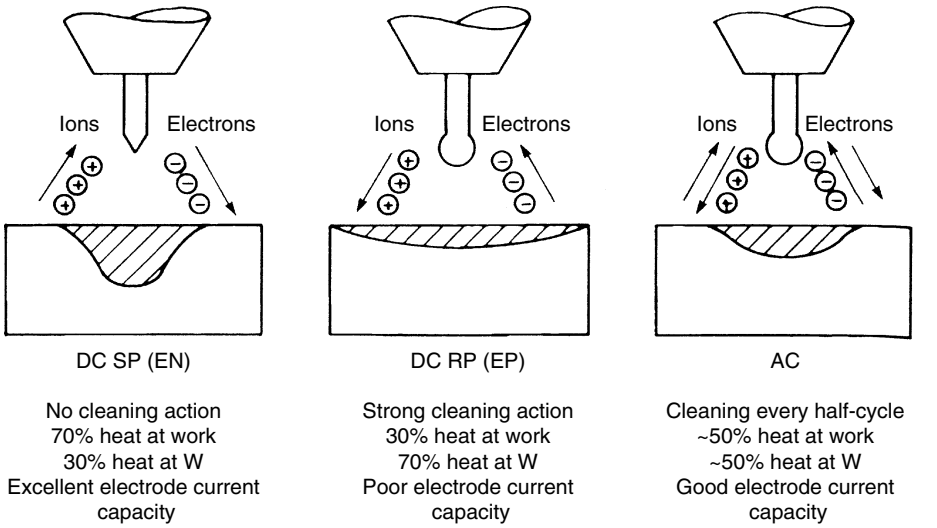

Figure 6.13 Schematic illustration summarizing the characteristics of the various operating modes for GTAW. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.11, page 204, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

However, these can both be overcome by using a "hot wire" variation in which the filler wire is heated resistively by being included in the circuit at a lower potential than the electrode or by using a special flux assist in *flux-assisted GTAW*.

Plasma Arc Welding. *Plasma arc welding* (PAW) is similar to gas–tungsten arc welding in that it, too, uses a nonconsumable tungsten electrode to produce an arc to a workpiece. The difference is that in plasma arc welding the converging action of inert gas at an orifice in the nozzle of the welding torch (see Figure 6.14) constricts the arc, resulting in several advantages over the GTAW process. These advantages include greater energy concentration (i.e., higher energy density) with attendant higher heating intensity, deeper penetrating capability, higher welding speeds, improved arc stability, and usually cleaner welds since the tip of the tungsten electrode cannot accidentally be touched to the workpiece to cause contamination. Figure 6.15 schematically compares the GTAW and PAW processes.

The plasma in PAW is created by the low-volume flow of argon through the inner orifice of the plasma arc torch. A high-frequency pilot arc established between the tungsten electrode and the inner nozzle ionizes this orifice gas and ignites the primary arc to the workpiece. When the workpiece is connected electrically to the welding torch such that it is of opposite polarity to the permanent electrode, the plasma is drawn to the workpiece electrically; the plasma generation is referred to as operating in the "transferred plasma arc" mode. When the workpiece is not connected electrically to the torch, and the plasma is simply forced to the workpiece by the force of the inert gas, the plasma

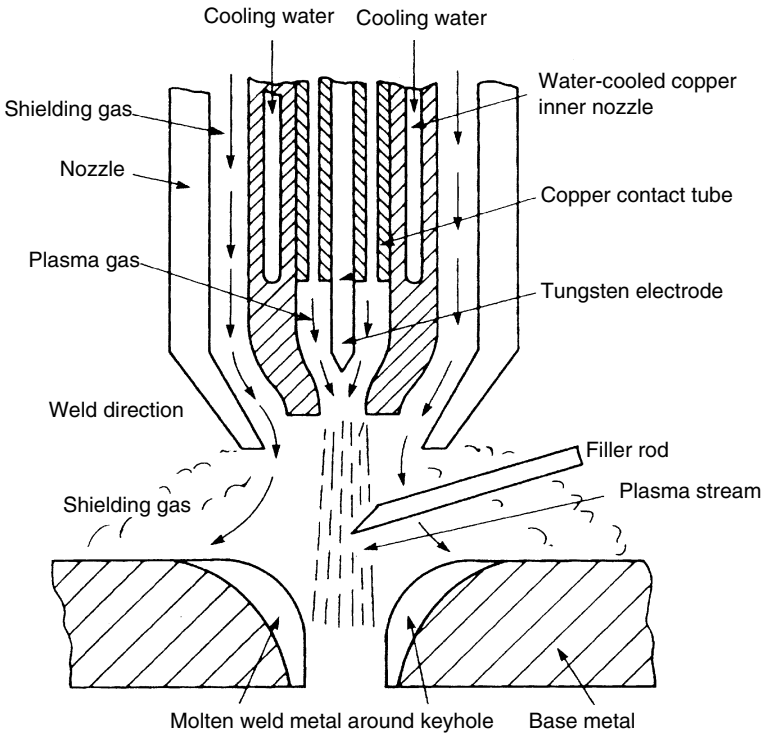

Figure 6.14 Schematic illustration of a plasma arc welding torch. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.12, page 205, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

generation is referred to as the "nontransferred plasma arc" mode (see Figure 6.16). The transferred arc mode is usually used for welding, while the nontransferred arc mode is used for thermal spraying (see Chapter 10, Subsection 10.2.5). Concentric flow of inert gas from an outer nozzle provides shielding to the arc and the weld in PAW. This shielding gas can be argon, helium, or argon mixed with helium or hydrogen.

Two distinctly different welding modes are possible with the plasma arc welding process, as they also are with the high-energy beam processes of laser beam and electron beam welding: the "melt-in mode" or "conduction mode" and the "keyhole mode." In the melt-in mode, heating of the workpiece occurs by conduction of heat from the plasma's contact with the workpiece surface inward. This mode is good for joining thin sections (e.g., 0.025–1.5 mm (0.001–0.006 in.)), for making fine welds at low currents, or for joining thicker sections (up to 3 mm (0.125 in.)) at high currents. In the keyhole mode, the high energy density of a very high-current plasma vaporizes a cavity through the workpiece and creates a weld by moving the keyhole, analogous to moving a hot wire through paraffin wax. Molten metal surrounding the intensely hot vapor cavity is drawn by surface tension or capillary forces to fill the cavity at the trailing edge of the weld pool. This mode is excellent for welding applications requiring

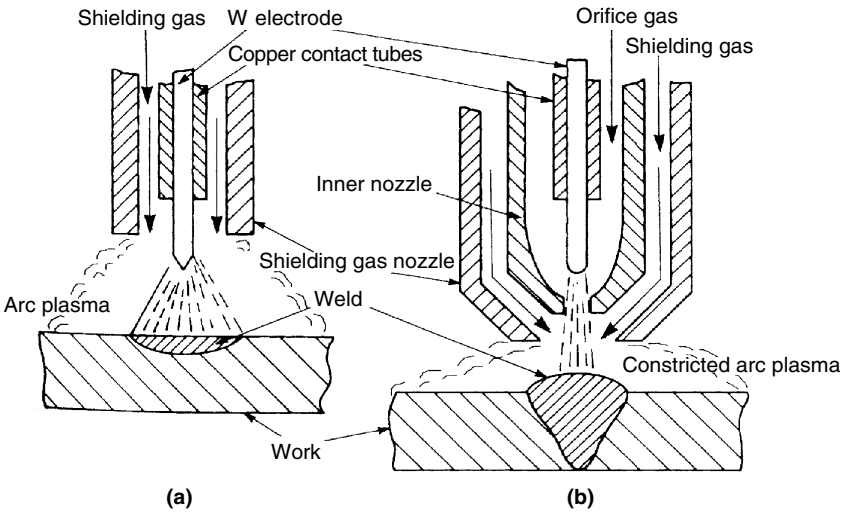

Figure 6.15 Schematic illustration comparing the (a) GTAW and (b) PAW processes. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.13, page 205, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

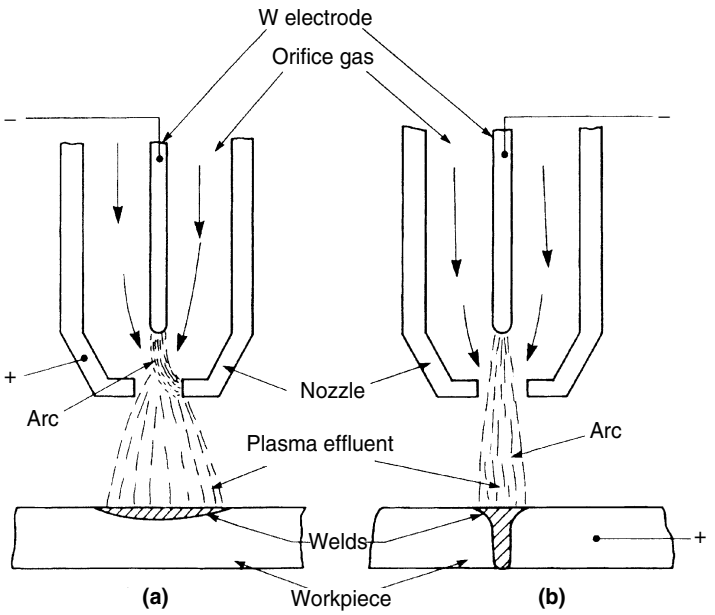

Figure 6.16 Schematic illustration showing the (a) non-transferred vs. (b) transferred arc modes of plasma generation. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.14, page 206, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

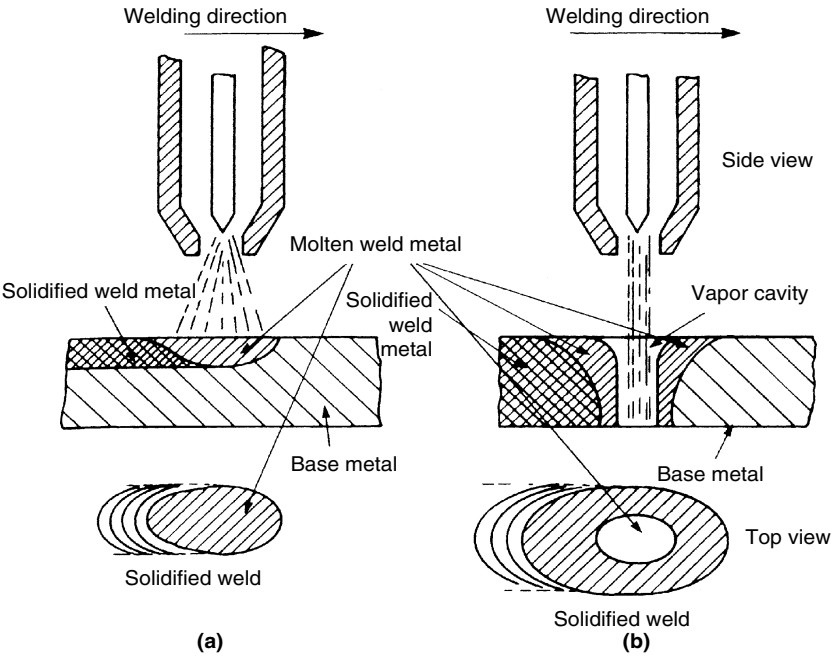

Figure 6.17 Schematic illustration of the (a) melt-in versus (b) keyhole modes in high-energy-density welding processes. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.15, page 207, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

deep penetration, to approximately 20 mm (0.8 in.). These two modes are shown schematically in Figure 6.17.

The single greatest disadvantage of PAW is the required equipment. Power sources, gas controllers, and torches are all complicated and expensive, and the torches tend to be large, making handling difficult during manual operation.

Consumable Electrode Arc Welding Processes

The six predominant consumable electrode arc welding processes are: (1) gas-metal arc welding (GMAW), (2) shielded-metal arc welding (SMAW), (3) flux-cored arc welding (FCAW), (4) submerged arc welding (SAW), (5) electrogas welding (EGW), and (6) electroslag welding (ESW). The gas-metal and electrogas welding processes use an inert gas shield provided from an external source, while the shielded-metal and flux-cored arc welding processes achieve shielding with gases generated from within the consumable electrode during welding. The submerged arc and electroslag welding processes achieve shielding of the molten weld metal with a molten slag or flux cover. Each of these processes is described in the following subsections.

Gas-Metal Arc Welding. The *gas-metal arc welding* (GMAW) process uses a continuous solid wire electrode and an externally supplied inert shielding gas. A

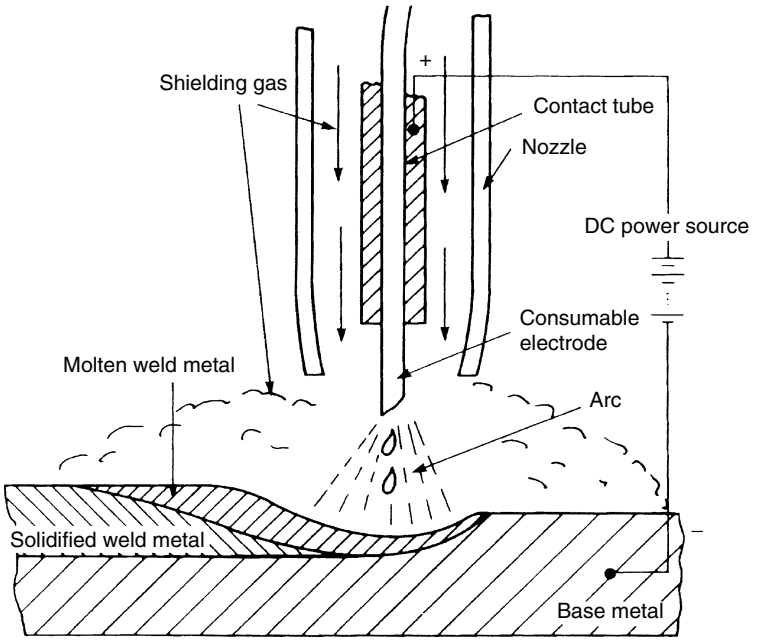

Figure 6.18 Schematic illustration of the gas-metal arc welding (GMAW) process. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Fig. 6.16, page 208, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlingon, MA.)

schematic of the process is shown in Figure 6.18. The consumable solid wire electrode provides all the filler to the weld joint. The externally supplied shielding gas plays dual roles in GMAW (as it does in the gas-shielded form of the FCAW and EGW processes). First, it protects the arc and the molten or hot cooling weld metal from air and, second, it provides desired arc characteristics through its effect on ionization. A variety of gases (e.g., argon, helium, carbon dioxide, and hydrogen, occasionally with a small amount of oxygen added) can be used, depending on the reactivity of the metal being welded, the design of the joint, and the specific arc characteristics that are desired. A variety of DC power sources can also be used, hooked up as shown in Figure 6.18. Either DCSP (DCEN) or DCRP (DCEP) may be used, depending on the particular wire and desired mode of molten metal transfer.

A distinct advantage of GMAW is that the mode of molten metal transfer from the consumable wire electrode can be intentionally changed and controlled through a combination of shielding gas composition, power source type, electrode type and form and feed rate into the arc, and arc current and voltage. There are three predominant metal transfer modes: spray, globular, and short circuiting. There is also a pulsed current or pulsed arc mode that is not specifically related to the molten metal transfer mode.

The spray transfer mode is characterized by an axial transfer of fine, discrete molten particles or droplets from the consumable electrode to the workpiece at rates of several hundred per second. The metal transfer is very stable, directional, and essentially

free of spatter.[20] Spray transfer is produced by welding in the DC electrode positive mode at high voltages (typically 27–30 v) and amperages above some critical value related to the wire's diameter. Argon or argon–helium mixtures are usually used when welding reactive metals like aluminum, titanium, and magnesium, while small amounts of carbon dioxide (e.g., 20%) or oxygen (e.g., 2%) are usually added when welding ferrous alloys to stabilize the arc and give the weld a better, more regular contour.[21]

The high arc energy and heat associated with the spray transfer mode limits its effectiveness for joining sheet gauge metals, but the strong directional spray (often referred to as "arc stiffness") can be useful for welding vertically up or down or overhead, all of which are said to be "out of position" compared to downward or "down-hand" on a horizontal plane.

Globular transfer is characterized by large globules or drops of molten metal being formed at the tip of the consumable electrode and then being released and carried to the workpiece and weld by gravity and/or arc forces. Globule formation is usually from about one per second to five per second. The large drop size tends to make out-of-position welding difficult, as there is no directed "push" to make the drops fight gravity. Spatter is usually considerable compared to spray transfer. When argon or argon–helium is used for shielding, welding currents must be kept low to achieve this mode. Carbon dioxide–rich gases are usually used when this mode is desired, however, since the spray transfer mode cannot be achieved regardless of the current level, yet high deposition rates and welding speeds can be achieved.

Unlike the spray and globular modes (which are known as "free-flight" modes) in the short-circuiting mode (which is known as a "bridging" mode), welding currents and voltages are kept low and the slow-forming globules at the tip of the consumable electrode are periodically touched to the weld puddle to cause their release through surface tension forces. This short-circuiting occurs at rates in excess of 50 per second and is best performed using specially designed power sources. The low currents required for this mode enable the welding of thin sections without melting through or overwelding. Out-of-position welding is facilitated by the direct transfer of the molten metal through contact. Spatter is minimized with this transfer mode.

Rather than using constant current during welding, as is usually the case, it is possible to superimpose intermittent high-amplitude pulses on a low-level steady current that maintains the arc. This is known as the "pulsed current" or "pulsed arc" mode. Here, "mode" refers to the mode of current and not the mode of molten metal transfer. Pulse rates typically run from one-half to five per second, with rates over this being of questionable value. This technique allows spray transfer to be obtained at appreciably reduced current levels during the high-amplitude pulses. Argon-rich gases are essential, and programmable power sources are required, but several advantages are obtained, including the use of relatively large-diameter elec-

[20] "Spatter" refers to residual molten metal that is expelled from the consumable electrode onto the workpiece but not into the weld pool. Spatter is a source of loss of useful energy and mass, so it is undesirable. Also, it is often necessary to remove spatter by chipping or grinding for either cosmetic or fit or fatigue resistance.

[21] The contour of a weld refers to the shape of its solidified crown or top bead. It is generally considered best if the contour is somewhat convex, with a smooth transition to the base metal, and uniform along its length.

trodes for higher deposition rates, suitability to thin or thick gauges, suitability for in- or out-of-position welding, and attractive weld crown bead appearance.

The globular, short-circuit, and pulsed-arc transfer modes use the direct current electrode negative operating (DCEN or DCSP) mode, while the spray transfer mode usually uses the electrode positive (DCEP or DCRP) mode to enhance melting of the consumable electrode. The various molten metal transfer modes are shown schematically in Figure 6.19.

In summary, the GMAW process offers flexibility and versatility, can be readily automated, requires less manipulative skill than SMAW, and enables high deposition rates (i.e., 5–20 kg (10–40 lb.) per hour) and efficiencies[22] (i.e., 70–85%). The greatest shortcoming of the process is that the power supplies[23] typically required are expensive.

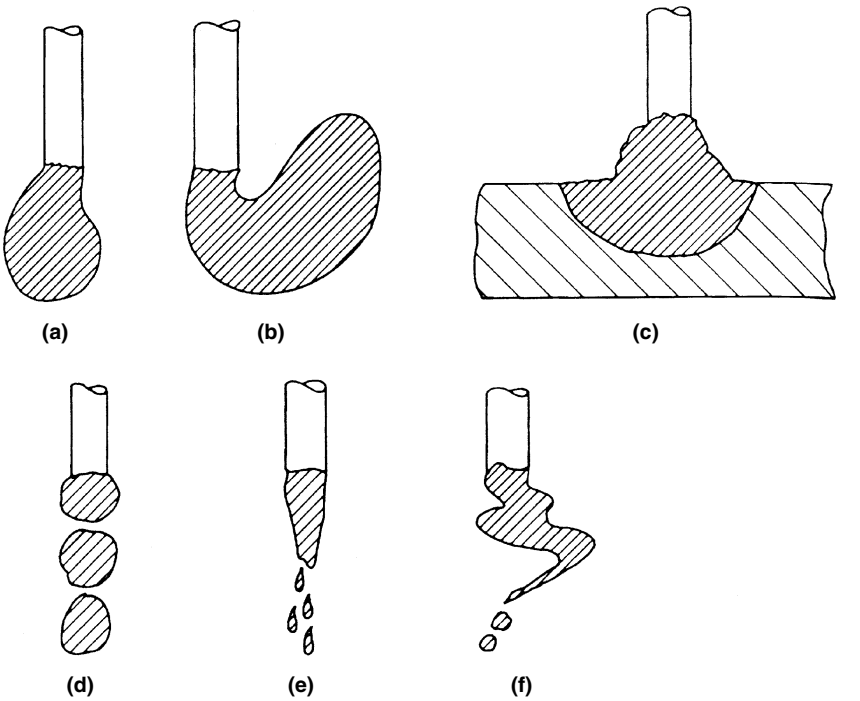

Figure 6.19 Schematic representation of the various molten metal transfer modes found in GMAW and other consumable electrode arc welding processes; (a) drop or globular transfer, (b) repelled globular transfer, (c) short-circuiting transfer, (d) projected spray transfer, (e) streaming spray transfer, and (f) rotating spray transfer. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.17, page 210, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

[22] "Efficiency" in this case refers to the efficiency with which energy available in the heat source is transferred to the workpiece for use in making the weld (see Subsection 6.4.6).

[23] Constant voltage (CV) power supplies are used. These and constant current (CC) types are described in various references (such as the AWS Handbook), but not here.

Shielded-Metal Arc Welding. The *shielded-metal arc welding* (SMAW) process is commonly known as the "stick welding process." As shown in Figure 6.20, metal coalescence is produced by the heat from an electric arc that is maintained between the tip of a flux-coated, or "covered," discontinuous consumable called a "stick" electrode, and the surface of the base metal being welded. A core wire conducts the electric current from a constant current power supply to the arc and provides most of the filler metal to the joint. Some portion of the arc heat is lost to the electrode by conduction, and some power is lost to I^2R heating of the electrode.

The covering, coating, or flux on an SMAW electrode (or, as will be described later, the core of an FCAW wire) performs many functions. First, it provides a gaseous shield to protect the molten metal of the weld from the air. This shielding gas is generated by the thermal decomposition of the coating, which may be of several types: cellulosic, which generates H_2, CO, H_2O, and CO_2; rutile (TiO_2), which generates up to 40% H_2; or limestone ($CaCO_3$), which generates CO_2 and CaO slag and little or no H_2 and so is known as a low-hydrogen type. The different types are selected for different applications, where hydrogen can or cannot be tolerated.[24] Second, the coating provides

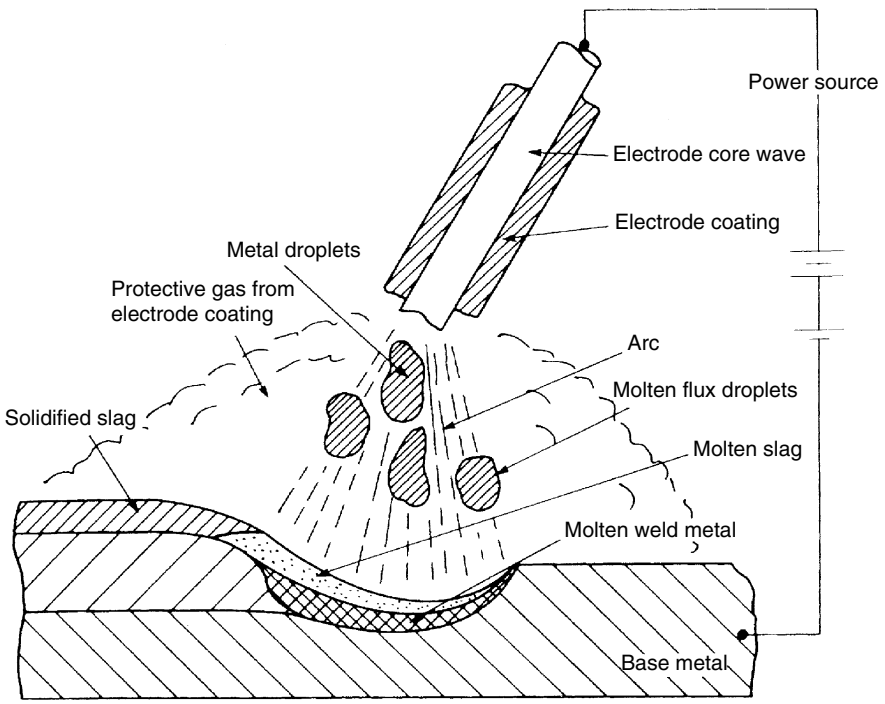

Figure 6.20 Schematic illustration of the shielded metal arc welding (SMAW) process. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.18, page 211, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

[24] Hydrogen-generating types of coatings should be avoided when hardenable (i.e., martensite-forming) steels are being welded, in order to avoid hydrogen embrittlement.

deoxidizers and fluxing or reducing agents (as molten compounds of metals) to deoxidize, denitrify, and cleanse the molten weld metal, as in metallurgical refining. Once solidified, the slag that is formed from the flux protects the already solidified but still hot and reactive weld metal from oxidation. It also aids out-of-position welding by providing a shell, or mold, in which molten weld metal can solidify. Third, the coating provides arc stabilizers in the form of readily ionizable compounds (e.g., potassium oxalate or lithium carbonate) to help initiate the arc and keep the arc steady and stable by helping conduct current by providing a source of ions and electrons. Fourth, the coating can provide alloying elements or grain refiners and/or metal fillers to the weld. The former help achieve and control the composition and/or microstructure of the weld, while the latter increase the rate of deposition of filler metal. There are actually several other important but more subtle contributions from the coating (e.g., friability of slag coating for easy removal, weld crown contour control, aiding out-of-position welding, low line-voltage tolerance, AC capability, and others), but these will not be detailed here.

SMAW can operate with DC power sources (with electrode positive or negative), or AC power sources, depending on the coating design. Typically, currents range from 50–300 amperes, largely based on electrode core wire diameter, at 10–30 volts, resulting in 1–10 kg (2–20 lb.) per hour deposition rates.

Advantages of SMAW are that it is simple, portable, and requires inexpensive equipment (i.e., power supply, electrode holder, and cables). The process is versatile, enabling joining or coating for restoring dimensions or enhancing wear resistance (i.e., hardfacing or wear-facing) for fabrication, assembly, maintenance, or repair, in the plant or in the field. Shortcomings of the process are that it offers only limited shielding protection and limited deposition rates compared to many other arc welding processes, and it is usually performed manually rather than automatically. Like all manual welding processes, but even more than most, SMAW requires considerable operator skill for the best results.

Flux-Cored Arc Welding. *Flux-cored arc welding* (FCAW) or "open-arc welding" is similar to SMAW in that it is self-shielding. However, the gas- and flux-generating ingredients are contained in the core of a roll-formed or drawn tubular wire, rather than on the outside of a core wire as a coating. The cored wire serves as a continuous consumable electrode, with the filler in the core fulfilling the same functions as the coating in SMAW, namely, providing shielding gases, slag-forming ingredients, arc stabilizers, and alloy additions and deposition-rate enhancers. The self-shielding provided by the generation of gases from the core through the arc is more effective than when such gases are generated from an external coating. By the time gas that is generated reaches the air to be swept away, it has fulfilled its shielding function. For this reason, FCAW is an excellent choice for welding in the field, and it is here that it got its name, "open-arc welding."

The FCAW process can also be operated in a gas-shielded mode, in which case it is closely related to the gas-metal arc welding (GMAW) process. Both use a continuous consumable electrode, both provide filler, and both use an externally provided inert gas to shield the arc and the weld metal. In either mode, FCAW can be operated with DC

power supplies, with the electrode positive or negative, depending on the particular wire type and formulation.

Figure 6.21 schematically illustrates the self-shielded and gas-shielded forms of FCAW. Process advantages include the following: high deposition rates (from 2–20 kg (5–40 lb.) per hour), with actual rates being high due to the continuous operation at higher currents than SMAW; larger, better-contoured welds than SMAW; portability; and excellent suitability for use in the field, even in extreme conditions.

Submerged Arc Welding. In the *submerged arc welding* (SAW) process, shown schematically in Figure 6.22, the arc and the molten weld metal are shielded from the air by an envelope of molten flux inside a layer of unfused granular flux particles. Since the arc is literally buried or "submerged" in the flux, it is not visible. As a result, the process is relatively free of the intense radiation of heat and UV-intensive light and of the fumes typical of most open arc welding processes, and the resulting welds are very clean. The SAW process uses a continuous solid wire electrode (or, in cases where very

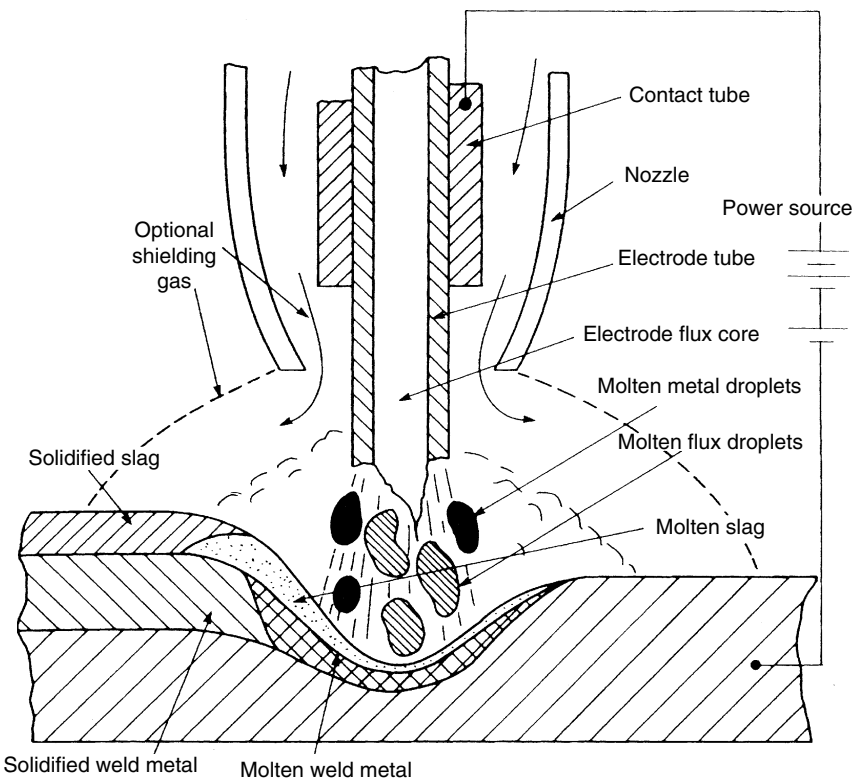

Figure 6.21 Schematic illustration of the flux-cored arc welding (FCAW) process, operating either self-shielded or gas-shielded. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Fig. 6.19, page 213, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

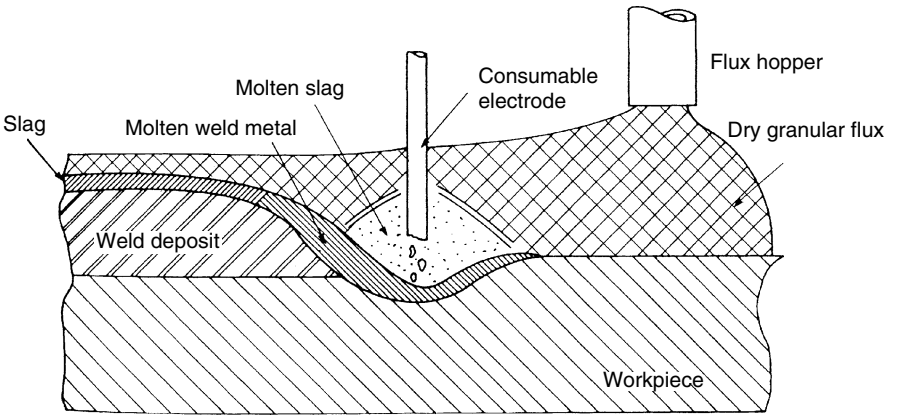

Figure 6.22 Schematic illustration of the submerged arc welding (SAW) process. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.20, page 213, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

high deposition rates are needed, multiple wires, twisted wires, or even thin strips) that is (are) consumed to produce filler. The efficiency of transfer of energy from the arc source to the workpiece is very high (usually greater than 90%), since losses from radiation, convection, and spatter are minimal to nonexistent.

The "sub-arc" process is always mechanized, as currents are very high (500 to more than 2000 amperes), deposition rate is very high (25–45 kg (55–100 lb.) per hour), and reliability is high. On the other hand, feedback must be by instrumentation as opposed to more common operator direct observation. Thin sections can be welded at very high velocities (up to 500 cm or 200 in. per minute), while very thick sections (up to 4–6 cm ($1\frac{1}{2} - 2\frac{1}{2}$ in.)) can be welded at lower velocities, even in the direct current electrode positive (DCRP) operating mode. At very high currents (over 1,000 A), AC is often used to avoid problems with "arc blow."[25] Because deposition rates tend to be high, and molten weld pools large, welding is restricted to flat or horizontal positions because of the effects of gravity.

The granular flux employed in the SAW process is specially formulated to control its "basicity index," which determines precisely how metallurgical refinement of the molten weld pool will occur, but which also affects bead appearance and release of solidified slag from the weld. Often, fluxes also contain additives to compensate for the loss of volatile alloying elements (e.g., Mn and Cr) from the filler. Approximately 1 kg of flux is consumed for every kilogram of filler deposited.

Electrogas Welding. The *electrogas welding* (EGW) process is a heavy deposition rate arc welding process. The process operates under an inert gas shield provided from a pressurized gas cylinder to a joint enclosed with water-cooled dams or "shoes" or

[25] "Arc blow" refers to the deflection of an arc by the induced electromagnetic fields in conductive materials, under what is known as the Lorentz force.

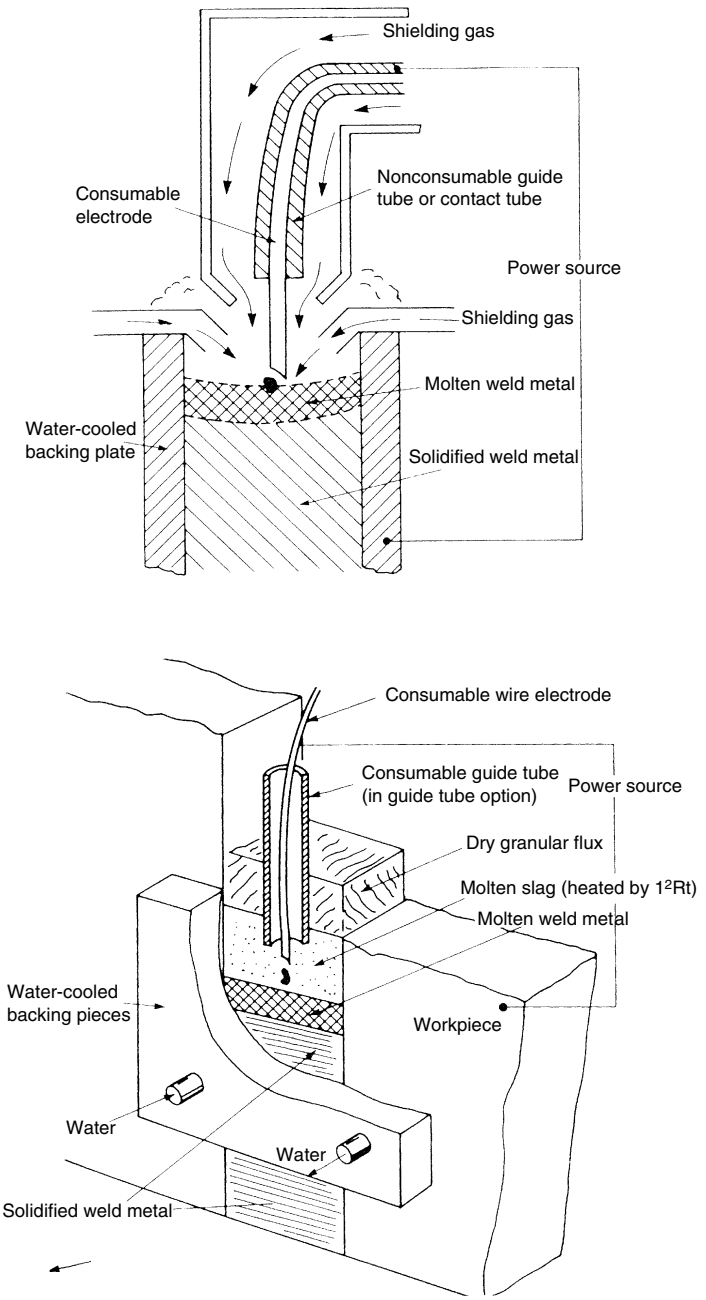

Figure 6.23 Schematic illustrations of the electrogas welding (EGW) (top) and electroslag welding (ESW) (bottom), processes. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Figs. 6.21 and 6.22, page 215, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

backing plates, as shown schematically in Figure 6.23a. Deposition rate can be as high as or higher than SAW and the quality of the deposit is excellent because of the extremely effective shielding afforded by inert gas. A drawback is that the process can only be used for welding vertically up, but this mode requires little joint preparation for fit.

Electroslag Welding. The *electroslag welding* (ESW) process is not actually a true arc welding process. The energy for melting the base metal and filler is provided by a molten bath of slag that is resistance heated by the welding current due to I^2R. The arc is used only to melt the flux initially, after being struck at the bottom of the joint. Welds are produced in the vertical-up direction (and, occasionally, in horizontal fillets), with the joint edges being melted and fused by molten weld filler metal contained in the joint by watercooled dams or backing plates, as shown schematically in Figure 6.23b. The molten flux or slag provides excellent protection to the weld, so welds are of very high metallurgical quality. Deposition rates are typically 7–13 kg per hour or 15–30 lb. per hour per electrode, and multiple electrodes are often used. In the so-called "guide tube" mode of this process, a consumable, thick-walled tube of the appropriate composition is used to provide additional filler as well as to guide the continuous wire electrode to the bottom of the joint. Here, deposition rates can easily reach 15–25 kg (35–55 lb.) per hour per electrode/guide tube.

6.4.4 High-Energy Beam Welding

The density of the energy available from a heat source for welding (or cutting) is often more important than the absolute source energy.[26] Two major types of high-energy-density welding processes are (1) *electron-beam welding* (EBW), and (2) *laser-beam welding* (LBW). Both processes use a very high-intensity beam as the heating source for welding, one in which the energy from the source is highly concentrated by electromagnetic or optical lenses, respectively. The energy density in these processes is approximately 10^{10}–10^{13} watts (W) per m^2 versus $5 \times 10^8 W/m^2$ for typical arc welding processes. Conversion of the kinetic energy of fast-moving electrons in EBW and photons in LBW into heat occurs as these particles strike the workpiece, leading to heating, melting, *and* vaporization in a highly localized area. Both processes usually operate in the keyhole mode (see Subsection 6.4.3), so penetration can be high, producing deep, narrow, parallel-sided fusion welds with narrow heat-affected zones and minimal angular distortion due to non-uniform weld metal shrinkage or thermal contraction.

The electron beam welding process is almost always performed autogenously, so joint fit must be excellent. If filler is needed for thick section welds, preplaced shims must usually be used, as getting wire down into a deep weld is difficult. Laser beam welding is usually done autogenously also, but can use wires as a filler. Shielding for the EBW

[26] The analogy of "energy density" as it applies to welding is like the concentration of sunlight into a focused spot by a magnifying glass. While the energy coming through the magnifying lens is the same as that in the spot, the density of energy in the spot is much higher. Hence, the peak temperatures attainable, and the rate of heating, are far greater when energy density is high.

process is provided by the vacuum (typically 10^{-3}–10^{-5} atmospheres) required to allow the beam of electrons to flow to the workpiece unimpeded by collisions with molecules comprising air. Shielding for the LBW process is accomplished with inert gases, either in so-called ''dry-boxes'' or from special shrouds over the vicinity of the weld puddle.

These two processes are shown schematically in Figures 6.24a and 6.24b, and comparative advantages and disadvantages are listed in Table 6.6.

6.4.5 Resistance Welding

As a group, *resistance welding* (RW) processes generate heat through the resistance to the flow of electric current through the parts being joined at the point of welding. The parts are an integral part of the electric circuit. As shown schematically in Figure 6.25, contact resistance, especially at faying surfaces, heats the area locally by I^2R or joule heating, resulting in melting and the formation of a ''weld nugget.'' For the process to work properly, the contact resistance must be higher at the point to be welded than anywhere else. Pairs of water-cooled electrodes (made of copper or copper alloyed with refractory metals, such as Cr, Zr, or W) to improve electrically induced erosion resistance) conduct current to the joint, apply pressure (by clamping) to improve contact (i.e., reduce the contact resistance) at the electrode-to-workpiece interface, and help contain the molten metal in the nugget, as it almost always tends to expand compared to the solid. The principal process variables are welding current (usually several thousand to tens of thousands of amperes), welding time (on the order of 1/6–1/3 second), electrode force (to force contact and resist molten metal expulsion), and electrode shape (to help concentrate current and pressure). Usually, the process is used to join overlapping sheets or plates, which may have different thicknesses.

At least six major types of welding processes rely on resistance heating to produce welds, with several variations within certain types, including (1) resistance spot welding (RSW); (2) resistance seam welding (RSEW), using high frequency (RSEW-HF) or induction (RSEW-I); (3) projection welding (PW); (4) flash welding (FW); (5) upset welding (UW), using high frequency (UW-HF) or induction (UW-I); and (6) percussion welding (PEW). Spot welding produces a discrete nugget by resistance heating with a single ''welding schedule.'' Nuggets or welds are usually produced directly under the electrodes but may not be if there is another more favorable (i.e., lower-resistance) path for the current. Spot welding usually requires access to both sides of the workpiece, but can be accomplished from one side, on the face of the workpiece, through the workpiece to produce a weld at the interface of the workpieces, through the workpiece farthest from the electrode, back through the workpieces to produce a second weld, and into a second electrode contacting the front face of the work, in what is known as ''series spot welding.''

Seam welding consists of a series of overlapping spots to produce an apparently continuous, potentially leak-tight seam. In projection welding, projections or dimples in overlapping joint elements are used to concentrate the current during welding, focusing the weld energy and helping locate the weld more precisely. Seam and projection weld arrangements are shown schematically in Figure 6.26.

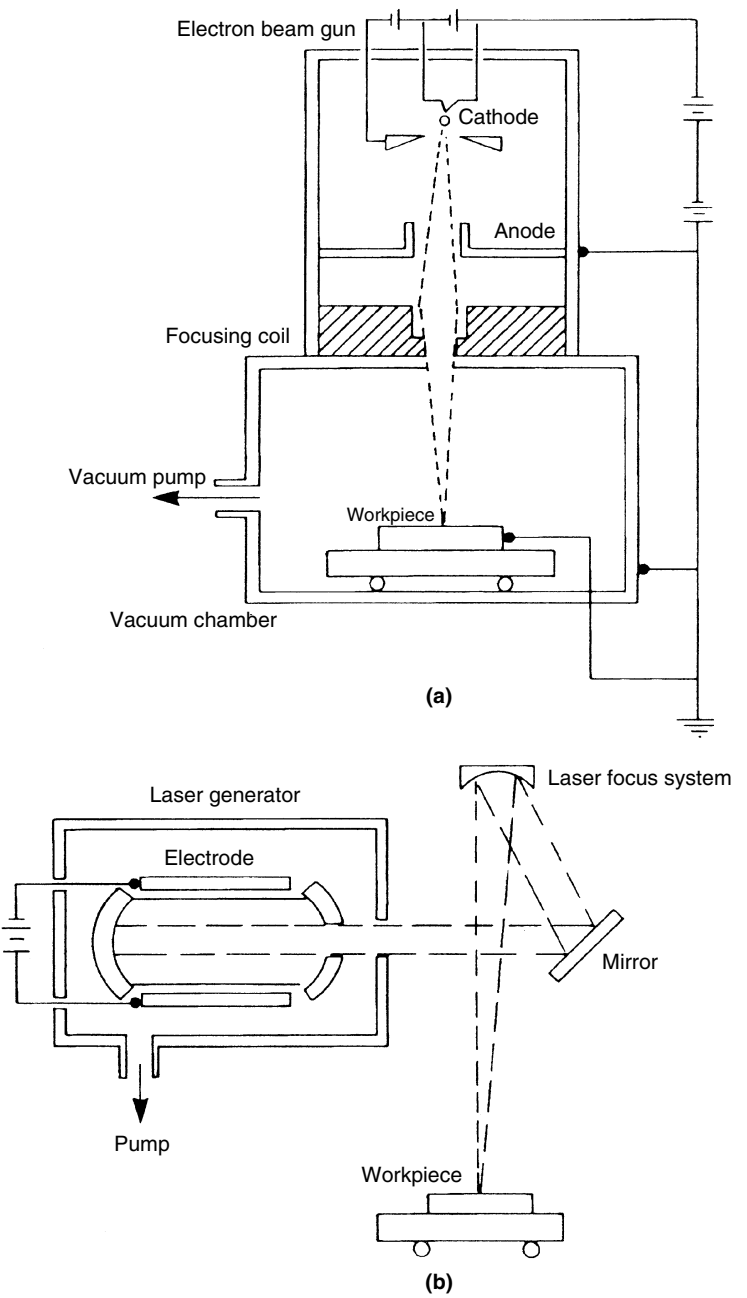

Figure 6.24 Schematic illustrations of the (a) electron-beam welding (EBW) and (b) laser-beam welding (LBW) processes. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.23, page 217, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

Table 6.6 Comparative Advantages and Disadvantages of the EBW and LBW Processes

EBW	*LBW*
• Deep penetration in all materials	• Deep penetration in laser-absorbent materials
• Very narrow welds, high depth/width	• Same
• High energy density; low heat input	• Same
• Capable of very high welding speeds	• Same
• Needs vacuum to operate unimpeded	• Can operate in air, inert gas, or vacuum
• Requires tight-fitting joints	• Same
• Almost impossible to add filler	• Filler can be added, if not too deep
• Capital equipment is expensive	• Same
• Very high electrical efficiency (99%)	• Very low electrical efficiency (<15%)
• Needs backup beam absorption	• Rarely needs backup beam absorption
• Generates x-rays from workpiece	• No x-ray generation

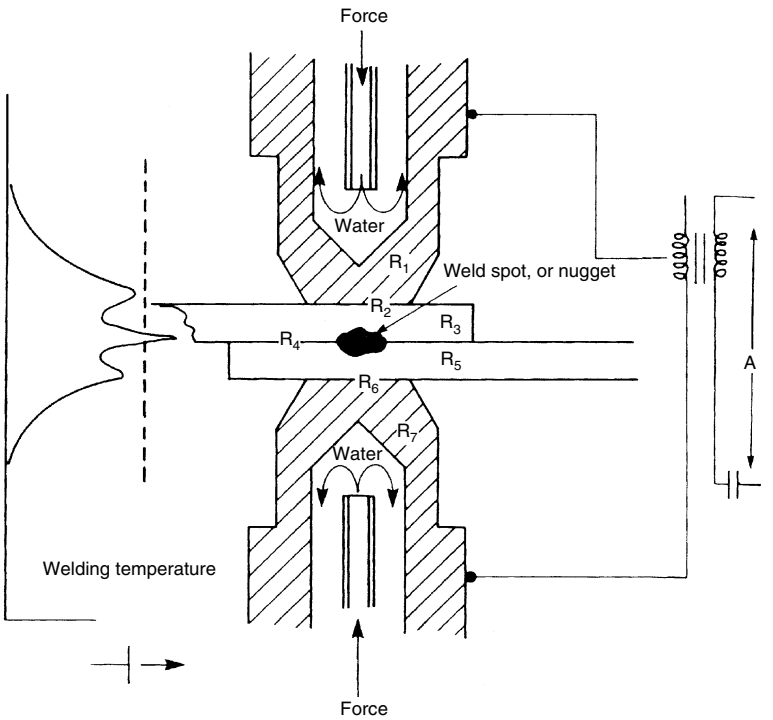

Figure 6.25 Schematic illustration of the resistance spot welding (RSW) process. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.24, page 218, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

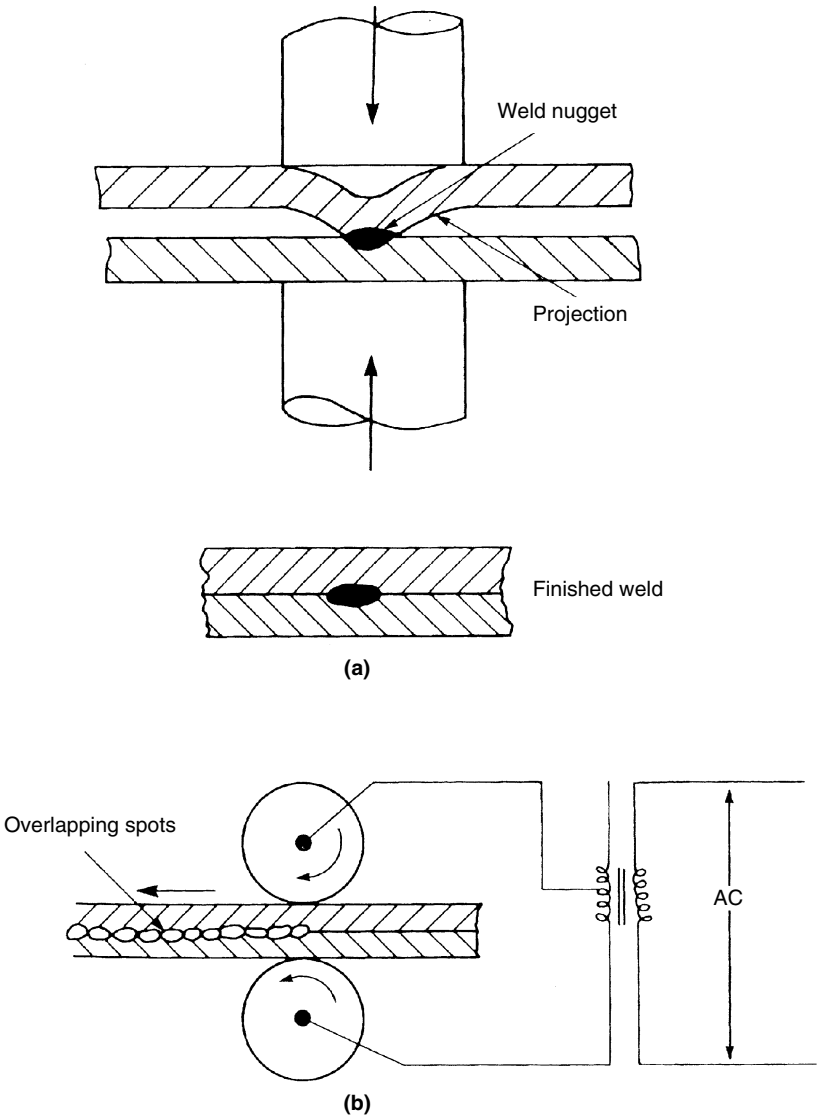

Figure 6.26 Schematic comparison of the (a) resistance seam welding (RSEW) and (b) projection welding (PW) processes. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Fig. 6.25, page 219, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

Flash welding is classified as a resistance welding process, but it is unique. Heating at the faying surfaces is by combined resistance and arcing. When the faying surfaces are heated to the welding temperature under the action of an applied current, force is applied immediately to consummate a weld. Molten metal is expelled, the hot base metal is plastically upset, a weld is produced, and a "flash" of frozen molten or hot resolidified metal

is formed. Closely related to flash welding is upset welding, with the major difference being the amount of gross plastic deformation or upsetting that is used to produce the weld. Figure 6.27 schematically illustrates flash welding, along with a typical flash weld.

Percussion welding (also known as "capacitor-discharge welding") produces welds through resistance heating by the rapid release of electrical energy from a storage device (e.g., capacitor).

In all resistance welding processes, the rate of heating is extremely rapid, the time for which the weld is molten is extremely short, and the rate of cooling to cause solidification is usually very rapid. This allows these processes to be used where heat input must be limited. On the other hand, resistance welding processes are, at the same time, capable of welding even the most refractory metals and alloys, because of the intense heating that can be made to occur by I^2R.

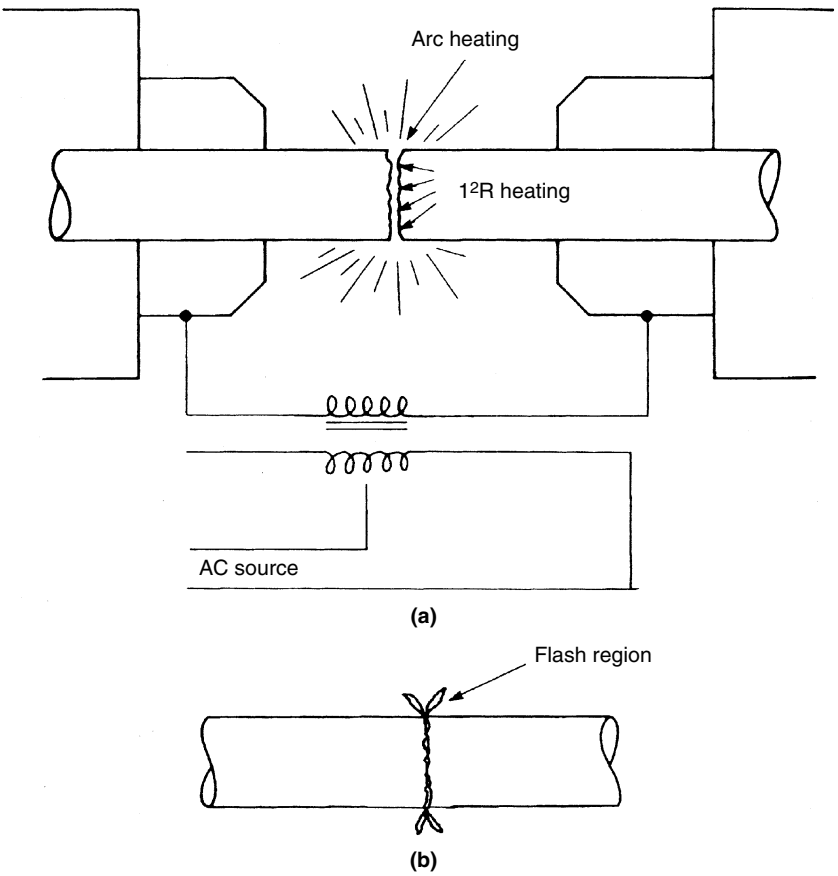

Figure 6.27 Schematic illustration of (a) the flash welding (FW) process and (b) typical resulting flash weld. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.26, page 220, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

6.4.6 Transfer Efficiency in Fusion Welding

There are many opportunities for energy to be lost between the welding heat source and the workpiece in fusion welding processes. The sum of all losses determines the *energy transfer efficiency* of the process. Figure 6.28 shows some of these losses. Anything that prevents or reduces a loss increases the energy transfer efficiency, η, to a maximum of 1.0 (100%). Some typical transfer efficiencies for various fusion welding processes are shown in Table 6.7. As an example, in the sub-arc process, transfer efficiency is very high because losses from radiation of light and heat, convection of heat to the air, and through spatter are eliminated. Transfer efficiency is important because it strongly affects the input of heat to the workpiece and the subsequent distribution of heat within the workpiece.

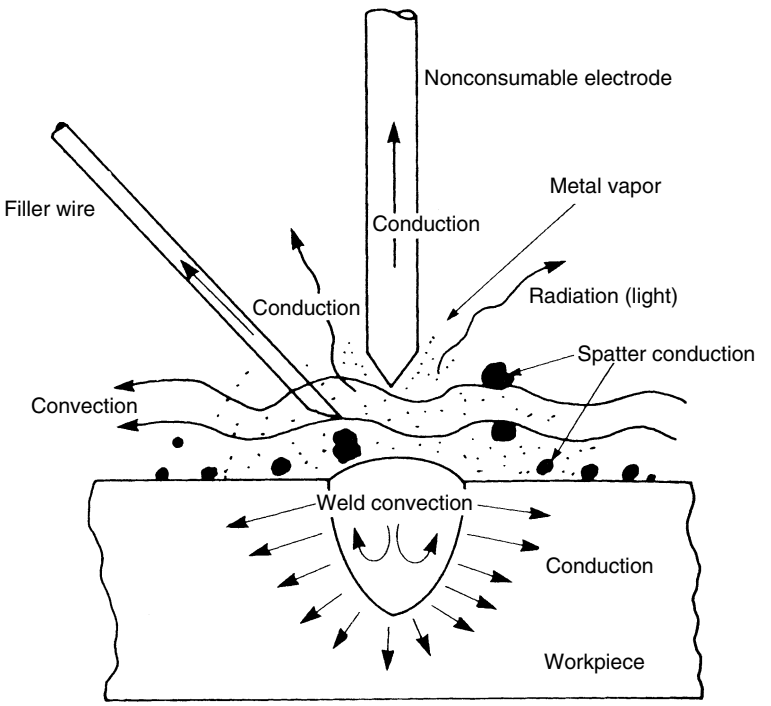

Figure 6.28 Schematic illustration of the various sources of losses of energy that lead to an energy transfer efficiency from the heat source to the workpiece of less than 100%. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.27, page 222, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

Table 6.7 Typical Energy Transfer Efficiencies for Fusion Welding Processes

Welding Process	*Transfer Efficiency*
Oxy-fuel gas	0.25–0.80[1] [0.50 typical]
Gas–tungsten arc	
Low current DCSP	0.40–0.60 [0.50 typical]
High current DCSP	0.60–0.80 [0.70 typical]
DCRP	0.20–0.40 [0.30 typical]
AC	0.20–0.60 [0.45 typical]
Gas–metal arc	
Globular transfer or short-arc mode	0.70–0.85 [0.75 typical]
Spray mode	0.65–0.75 [0.65 typical]
Shielded-metal arc	0.65–0.85 [0.75 typical]
Flux-cored arc	0.65–0.85 [0.75 typical]
Submerged arc	0.85–0.98 [0.90 typical]
Electrogas	0.70–0.85 [0.75 typical]
Electroslag	0.55–0.85 [0.70 typical]
Electron beam	
Melt-in mode	0.70–0.85 [0.80 typical]
Keyhole mode	0.80–0.95 [0.90 typical]
Laser beam	
Melt-in mode/reflective metal	0.005–0.10
Melt-in mode/absorptive metal	0.25–0.50
Keyhole mode	0.50–0.75

6.5 NON-FUSION WELDING PROCESSES

6.5.1 General Description of Non-Fusion Welding Processes

Non-fusion welding processes accomplish welding by bringing atoms (or molecules in polymers) of the materials being joined to equilibrium spacing principally through plastic deformation due to the application of pressure at temperatures below the melting point of the base materials, without the addition of filler that melts. Often some heat is generated by or supplied to the process to allow plastic deformation to occur at lower stresses and accelerate interdiffusion without causing, or at least depending upon, melting. While other sources of heat are possible, mechanical heating is the most common and includes friction sources[27] and pressure sources. Both actually produce heat as the result of the work done in deforming material, but on a microscopic scale for friction processes and on a macroscopic scale for the pressure processes.

[27] Naturally, friction processes also involve pressure, since the force of friction arises from the product of the applied normal force and the coefficient of friction, which is determined by the topographic and chemical state of the surface (i.e., $F = \mu N$).

As shown in Table 6.2, the eight major non-fusion welding processes are (1) cold welding (CW), (2) forge welding (FOW), (3) hot pressure welding (HPW), (4) roll welding (ROW), (5) explosion welding (EXW), (6) friction welding (FRW), (7) ultrasonic welding (USW), and (8) diffusion welding (DFW). There are variations of several of these specific types. Cold welding, forge welding, hot pressure welding, roll welding, and explosion welding all rely on substantial pressure to cause gross, macroscopic plastic deformation to produce a weld. Fairly substantial volumes of material, and moles of atoms, are moved to establish needed material continuity. Friction and ultrasonic welding rely on friction to cause heating and bring atoms or molecules together by microscopic plastic deformation to produce a weld. Much smaller volumes of materials are generally moved. Diffusion welding relies on heating to accelerate solid-state diffusion to produce welds through atomic-level mass transport. Pressure can play a minor role.

Non-fusion welding processes, as a group, offer several advantages over fusion processes. The general absence of melting and, typically, the low heat involved minimally disrupt the microstructure of the materials being joined. As shown in Figure 6.8b, there is no fusion zone or partially melted zone and, usually, a minimal heat-affected zone. By precluding the need for melting, intermixing of the materials involved in the joint is minimal on a macroscopic scale, so materials of dissimilar compositions can often be joined. The joint resulting from non-fusion welding typically has quite high efficiency. Process disadvantages relate to the surface preparation and tooling required to produce acceptable joints, and difficulties with inspecting and repairing defective joints.

6.5.2 Cold and Hot Pressure Welding Processes

There are really only two pressure welding processes that are accomplished cold, *cold welding* and, possibly, *cold roll welding*. Cold welding (CW), as the name implies, uses (usually substantial) pressure at room temperature to produce coalescence of materials through substantial plastic deformation at the weld. Besides high pressure, extremely clean surfaces are required (as described in Subsection 6.2.4). The process works best for ductile metals such as aluminum, copper, many of the brasses and bronzes, nickel, some nickel–copper or copper–nickel alloys, lead, and the precious metals (i.e., gold, silver, platinum, palladium, and rhodium). Welding of dissimilar metals (such as aluminum to copper) is also possible, whereas such combinations often cannot be welded by fusion processes! Cold welding is normally difficult to accomplish consistently in production, but it is a viable option for joining in space where freedom from oxidation is no problem.

In *roll welding* (ROW), pressure is applied to the elements of the joint to be welded through rollers, and such pressure can be applied while the base materials are at room temperature (i.e., cold). Roll welding is rarely performed without heat, however, as the forces (and mechanical power) needed to cause sufficient plastic deformation can be very high. Roll cladding of ductile metals, for example, aluminum onto copper or copper onto stainless steel (as in Revere cookware), is done this way, however.

To reduce the forces needed to cause the gross plastic deformation required to produce non-fusion welds, heat is usually used. Heating base metals or alloys also allows dynamic recrystallization[28] and attendant grain boundary migration to take place and enhances diffusion, thereby facilitating weld formation.

Hot pressure welding processes include hot pressure welding, forge welding, and hot roll welding. In *hot pressure welding (HPW),* of which there actually a few variations depending on by what means and at what point in the process heat is applied, coalescence of metals is accomplished with the application of heat and pressure sufficient to cause plastic deformation. Often, a vacuum or inert shielding medium is used to prevent oxidation that would impede bonding. A close relative of HPW is *forge welding* (FOW). In this process, heating takes place in air in a forging press or forging hammer, and pressure is applied progressively or with repeated blows. Plastic deformation at the interface between pieces being welded is extensive. This is an extremely old method of welding, being the basis for early iron making and blacksmithing. To facilitate bonding, a flux is often used at the faying surfaces to remove oxides. *Hot roll welding* (ROW) is performed as described for cold roll welding, except that the work is heated to reduce the material's flow stress and facilitate plastic deformation.

Explosion welding (EXW) is a pressure welding process that represents a special case. In explosion welding, the workpieces usually start out cold but heat up significantly and extremely rapidly, very locally at their faying surfaces, during the production of the actual weld. As shown schematically in Figure 6.29a, the controlled detonation of a properly placed and shaped explosive charge causes the workpieces to come together extremely rapidly at a low contact angle. When this occurs, air between the workpieces is squeezed out at supersonic velocities. The resulting jet cleans the surfaces of oxides and causes localized but rapid heating to high temperatures. The result is a metallurgical bond. The weld-bond line of explosion welds is typically very distorted locally, as shown schematically in Figure 6.29b.

6.5.3 Friction Welding Processes

Friction welding (FRW) processes use machines that are designed to convert mechanical energy into heat at the joint to be welded. Coalescence of materials occurs under the compressive contact of workpieces moving relative to one another linearly or in rotation. Figure 6.30a schematically illustrates one embodiment of the friction welding process. Because rotation is frequently used, at least one of the parts involved in the joint has an approximately circular cross-section. Frictional heating occurs at the

[28] *Dynamic recrystallization* is the nucleation and growth of new, strain-free, equiaxed grains from grains that are subjected to substantial strain as the strain is being applied. Provided the prevailing temperature is at some reasonable fraction of the base material's absolute melting (or homologous) temperature, say >55–60%, this process will occur spontaneously, or "dynamically." If the temperature is below this level, recrystallization will only occur when the temperature is raised to the same level as a post-deformation heat-treating process known as a "recrystallization anneal."

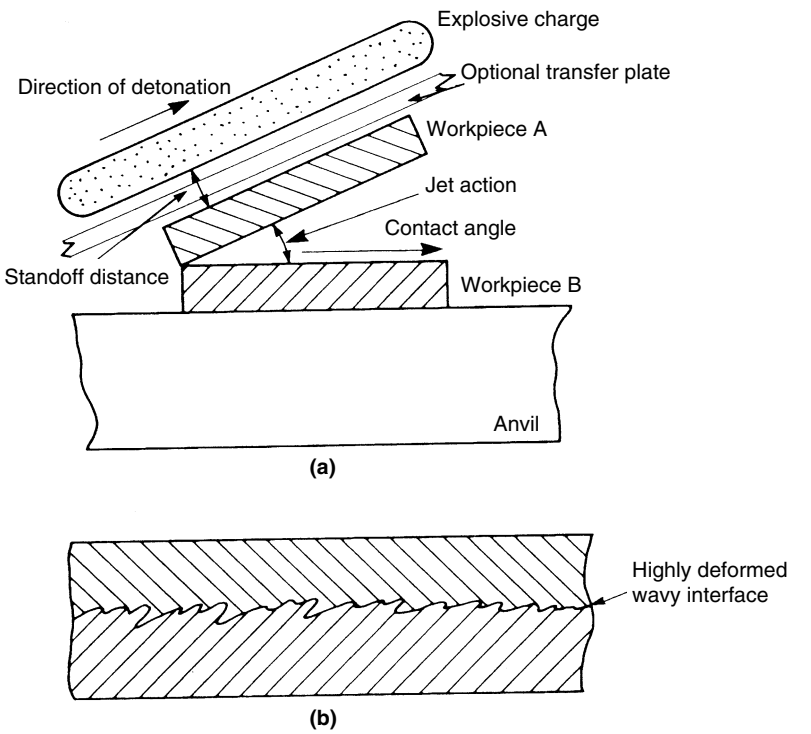

Figure 6.29 Schematic illustration of (a) explosion welding (EXW) and (b) the typical "disturbed" interface of explosion welds. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Fig. 6.28, page 224, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

interface between the parts as they are brought into contact under pressure, raising the temperature of the material to a level suitable for forging. Axial pressure forces hot metal out of the joint, disrupting and removing oxides and other surface impurities and producing upset (as shown in Figure 6.30b).

Two predominant techniques are used for friction welding. In the first, more conventional technique, known simply as *friction welding,* the moving part is held in a motor-driven collet and rotated at a constant speed against a fixed part, while an axial force is applied to both parts. Rotation is continued until the entire joint is suitably heated and then simultaneously the rotation is stopped and an upsetting force is applied, producing a weld. Key process variables are rotational speed, axial force, welding time, and upset force or displacement. In the second technique, called *inertia welding,* energy is stored in a flywheel connected to a motor through a clutch and to one of the workpieces by a collet. A weld is made by applying axial force through the rotating part to a stationary part while the flywheel decelerates, transforming its kinetic energy into heat at the faying surfaces. When done properly, the weld is completed when the flywheel stops. Key process variables are the flywheel moment of inertia, flywheel rotational speed, axial force, and upset force. The actual process for

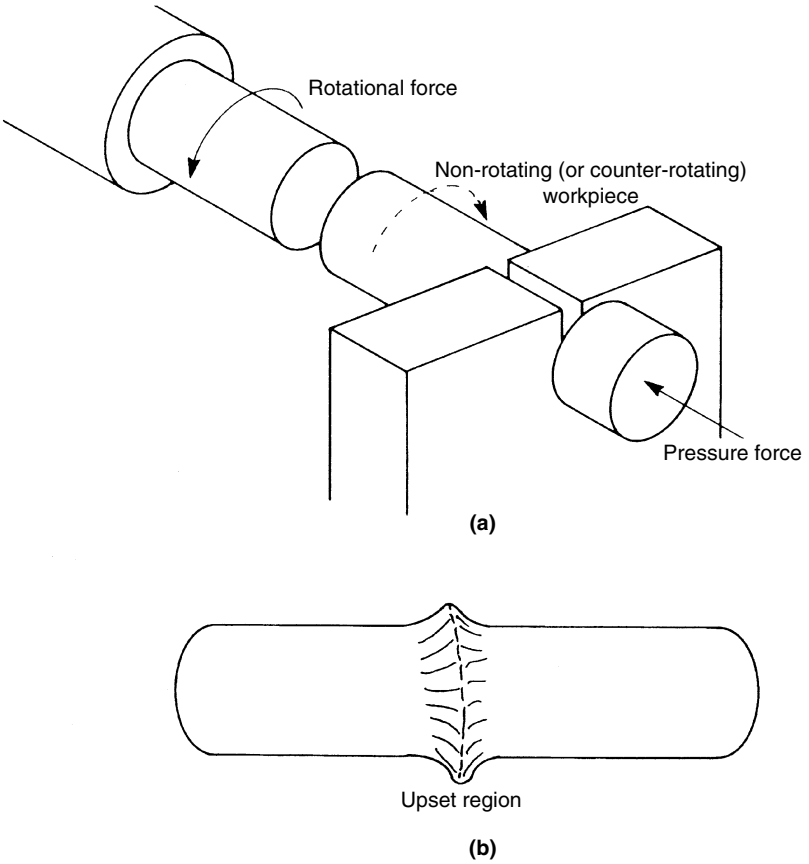

Figure 6.30 Schematic illustration of (a) a typical set-up of friction welding (FRW) and (b) a typical weld. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.29, page 225, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

both techniques is usually automated. Some rotational friction welding processes are called "spin welding."

It is also possible to accomplish friction welding using reciprocating linear or angular motion while joint components are held in contact under pressure. The source of motion can be pure mechanical vibration or ultrasonically induced vibration. These processes are called *vibration,* or *linear* or *angular vibration welding,* and *ultrasonic welding,* respectively.

A relatively new approach employs a rapidly rotating spindle-driven tool tip held between pieces to be welded under lateral pressure. The friction created between the tool and the workpieces literally stirs the base materials together, in the solid state, to produce a weld. The process is known as *friction stir welding*. Figure 6.31 schematically illustrates friction stir welding.

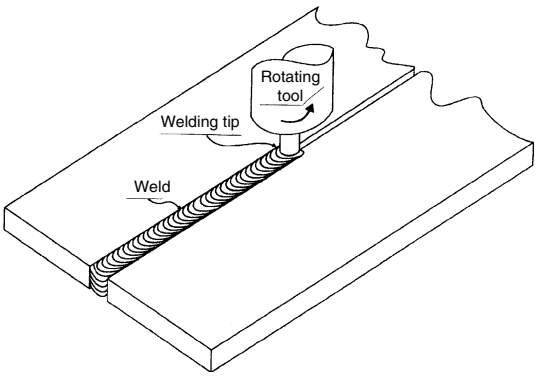

Figure 6.31 Schematic illustration of the friction stir welding (FSW) process. (Reprinted from *Principles of Welding: Processes, Physics, Chemistry & Metallurgy of Welding*, Robert W. Messler, Jr., John Wiley & Sons, New York, NY, Fig. 4.15, page 114, 1999, with permission.)

6.5.4 Diffusion Welding Processes

Diffusion welding (DFW) is a specialized process that is used predominantly when unique metallurgical characteristics are needed from the joining process. The process is frequently called "diffusion bonding," but this term is actually more encompassing than the process of diffusion welding, in which there is no melting. It also includes a bonding process that relies on interdiffusion between base materials with a liquid (albeit often only a transient liquid) phase being present. In any case, the process involves interdiffusion between the materials making up the joint. Diffusion kinetics is almost always accelerated by elevating the temperature and applying pressure. Heating can be accomplished using a furnace, vacuum retort, vacuum or inert gas autoclave; a hot platen press; or by resistance or induction. Pressure can be applied by dead weight loading, a press, differential gas pressure or differential thermal expansion of the parts to be joined, or the tooling holding or backing the parts. Uniaxial methods of applying pressure limit welding to flat, parallel, planar surfaces roughly perpendicular to the direction of load application. Isostatic pressurization, using encapsulation, or "canning," offers better pressure uniformity and is applicable to more complexly shaped parts. The principal purpose of applying pressure is to obtain contact at the faying surfaces to be joined. This contact occurs initially by plastic deformation of microscopic asperities, and later by creep.

Components to be diffusion-welded must be specially designed and carefully processed to produce consistently successful joints. The process is economical only when close dimensional tolerances, expensive materials, or special material properties are involved. Even then, not all metals can be easily—or effectively—diffusion welded or bonded. One excellent example, however, is titanium for aerospace applications. Titanium diffusion welds well because its oxide is soluble in the solid metal prior to melting, so it does not hinder metal-to-metal contact.

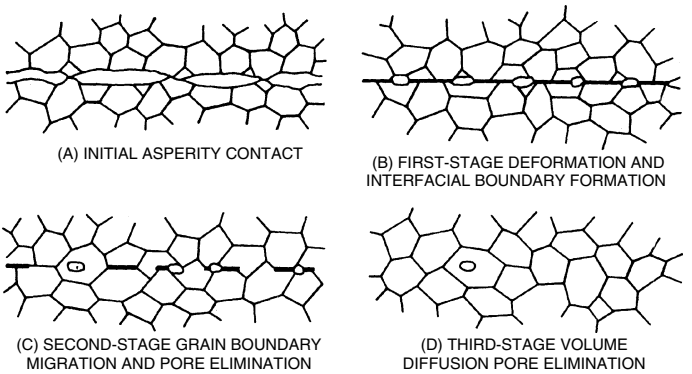
(A) INITIAL ASPERITY CONTACT
(B) FIRST-STAGE DEFORMATION AND INTERFACIAL BOUNDARY FORMATION
(C) SECOND-STAGE GRAIN BOUNDARY MIGRATION AND PORE ELIMINATION
(D) THIRD-STAGE VOLUME DIFFUSION PORE ELIMINATION

Figure 6.32 Schematic representation of the diffusion welding (DFW) process, showing (a) initial asperity contact, (b) first-stage plastic deformation and interfacial boundary formation, (c) second-stage grain boundary migration and pore elimination, and (d) third-stage volume diffusion pore elimination. (Reprinted from *Welding Handbook*, Vol. 2: *Welding Processes*, 8th ed., American Welding Society, Miami, Fl, 1991, with permission.)

Diffusion welding or bonding has the potential to produce "perfect" welds, with no fusion zone and no heat-affected zone as such—just unaffected base metal. Resulting joints are 100% efficient. But, the catch is that stringent process control is a must, inspection is difficult, and repair is impossible.

Figure 6.32 schematically illustrates diffusion welding.

In summary, non-fusion welding processes offer a valuable alternative to fusion welding processes, enabling the joining of difficult (often fundamentally dissimilar) materials to fairly precise tolerances, with little or no heat effect in the base materials.

6.6 WELD JOINT DESIGN

6.6.1 General Description of Weld Joint Design

Welding is always used to produce structural joints except, perhaps, when it is used to apply a hard-facing alloy to a structural part to improve that part's resistance to wear. (In fact, even the joint or interface between a hard facing overlay and the substrate must be structural if the overlay is to survive the loads the underlying part must survive.) Thus, it is no surprise that joint design is critical to the successful application of welding. The design involved must address the obvious structural conditions (i.e., types, magnitudes, and durations of all pertinent loads) but also the effects of the process itself (especially the heat of fusion welding) on the properties and dimensional integrity of the surrounding structure. The design of a joint for welding, as for other joining processes, should be selected primarily on the basis of load-carrying requirements. Especially in welding, however, variables in the design and layout of joints can have profound effects on the economics of the process, sometimes making or breaking the final decision on the joining approach.

So, without attempting to cover the subject of weld joint design exhaustively in the general context of this book, it is worth considering some general design guidelines. As a first guideline, *always select the joint design that requires the least amount of weld metal*. This will minimize distortion and residual stresses in the welded structure caused by weld shrinkage during solidification, and due to thermal expansion and contraction under severe temperature gradients during heating to produce the weld pool and cooling to produce the final weld. Where possible, use square grooves (see Subsection 6.6.3) and welds that only partially penetrate the joint. Partial penetration welds leave unmelted material in contact throughout welding to help maintain dimensions. They also prevent weld metal loss due to drop-through under the force of gravity. Use lap and fillet welds instead of groove welds when fatigue is not a design consideration. Use double-V or double-U instead of single-V or single-U groove welds on thick sections to reduce the amount of weld metal and control distortion. For corner welds in thick sections where fillet welds are not adequate, beveling of both members should be considered to reduce the tendency for lamellar tearing (in steels).[29]

Finally, always design an assembly and its joints for good accessibility for any welding and inspection that will be required.

6.6.2 Size and Amount of Weld

Overdesign is a common error in welded structures, as is overwelding in production. (It is not true that "if a little is good, a lot is better" in the case of welding!) Control of weld size and the amount of weld (i.e., weld length) begins in design but must be maintained during assembly and welding in production or construction. Overdesign and overwelding both lead to excessive and unnecessary cost, and are as likely to lead to structural problems from adverse effects of heat on the base materials (or from residual stresses, for example) as to increase structural integrity. Welds should be specified to adequate but minimum size and length for the forces to be transferred. Oversize welds may cause excessive distortion and higher residual stresses, without improving suitability. The size of a fillet weld is especially important because the amount of weld metal required to be deposited increases as the square of the weld size increases.

For equivalent strength, a continuous fillet weld of a given size is usually less costly than a larger-size intermittent fillet weld. Also, there are fewer weld starts and terminations that are potential sites for flaws. An intermittent fillet weld can be used in place of a continuous fillet weld of minimum size when a static loading condition exists. An intermittent fillet weld should not be used under cyclic fatigue loading. For automatic welding, continuous welding is preferred.

Welds should always be placed in the section of least thickness, and the weld size should be based on the load or other requirements of that section. The amount of welding should be kept to a minimum to limit distortion and internal stresses and,

[29] *Lamellar tearing* is tearing in the plane of a plate caused by tensile stresses acting perpendicular to the plane of that plate and aggravated by the presence of non-metallic stringer-type inclusions in the plate.

consequently, the need for straightening and stress relieving. Welding of stiffeners or diaphragms should be limited to that amount of welding required to safely carry the imposed load, and no more.

Figure 6.33 schematically illustrates the key concepts of weld size and amount.

Obviously, there are many more considerations important in the design of welds, but these give some appreciation of the problems. Details on weld size and lengths can be found in special works by Blodgett (1975) and in various standards of the American Welding Society for specific applications (e.g., bridges, railroads, shipbuilding, etc).

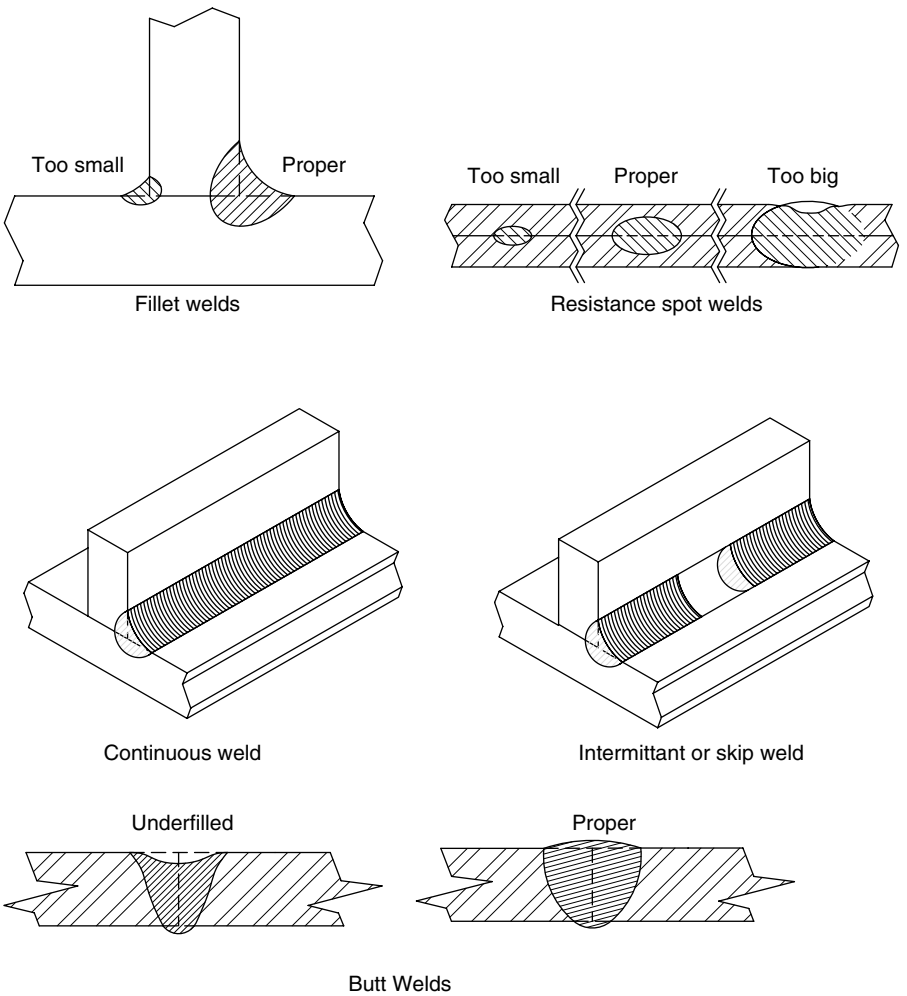

Figure 6.33 Schematic illustration showing various sizes and amounts of welding, as used in welded joint design, including fillet welds (top row, left), resistance spot welds of various sizes (top row, right), continuous and intermittent or skip welds (middle row, left and right), and underfilled and proper fusion butt welds (bottom row, left and right).

6.6.3 Types of Weld Joints

The loads in a welded structure are transferred from one member to another member through welds placed in joints. The type of joint, or the joint geometry, is predominantly determined by the geometric requirements or restrictions of the structure and the type of loading to be tolerated. Accessibility for welding, process selection, accessibility for inspection, and cost constraints are other factors affecting the choice of joint type.

The fundamental types and basic designs of joints used in welding are shown schematically in Figures 6.34 and 6.35. The fundamental types of welds (shown in Figure 6.34) include (a) groove welds (which require groove preparation by torch or exothermic cutting, electrode cutting, sawing, machining, or grinding and filling with one or more weld passes); (b) fillet welds (which usually do not require preparation, just single or multiple weld bead deposition); (c) plug welds (which require weld deposits to be made in preplaced drilled or punched or pierced holes to tie one plate to another); and (d) surfacing welds (which require overlay of weld metal to restored material lost to wear or other means, or to improve wear or corrosion resistance). The five basic joint designs used in welding (shown in Figure 6.35) are: (a) the butt joint, (b) the corner joint, (c) the edge joint, (d) the lap (or overlap) joint, and (e) the tee joint. Within these five types there are full- and partial-penetration, and continuous and discontinuous types, with either groove-filling or fillet welds. Joint preparations can involve single or double grooves with V-, U-, or J-shapes, or fillets with or without pre-prepared single or double bevels of various shapes, as can be found in handbooks on welding (see bibliography section).

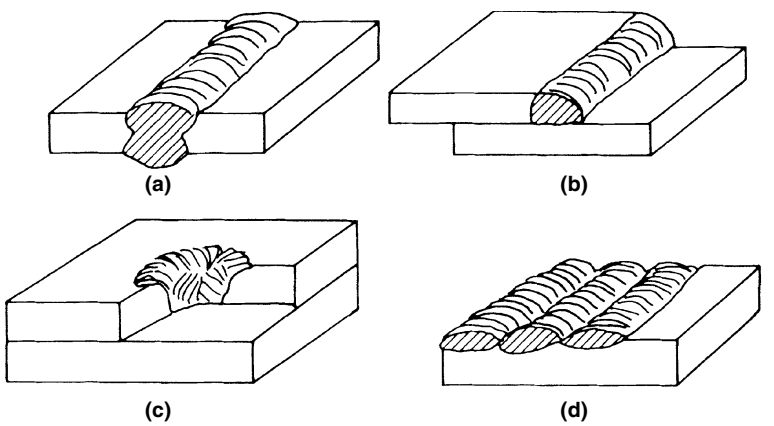

Figure 6.34 Schematic illustration of the fundamental types of welds, including (a) groove weld, (b) fillet weld, (c) plug weld, and (d) surfacing weld. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 6.30, page 228, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

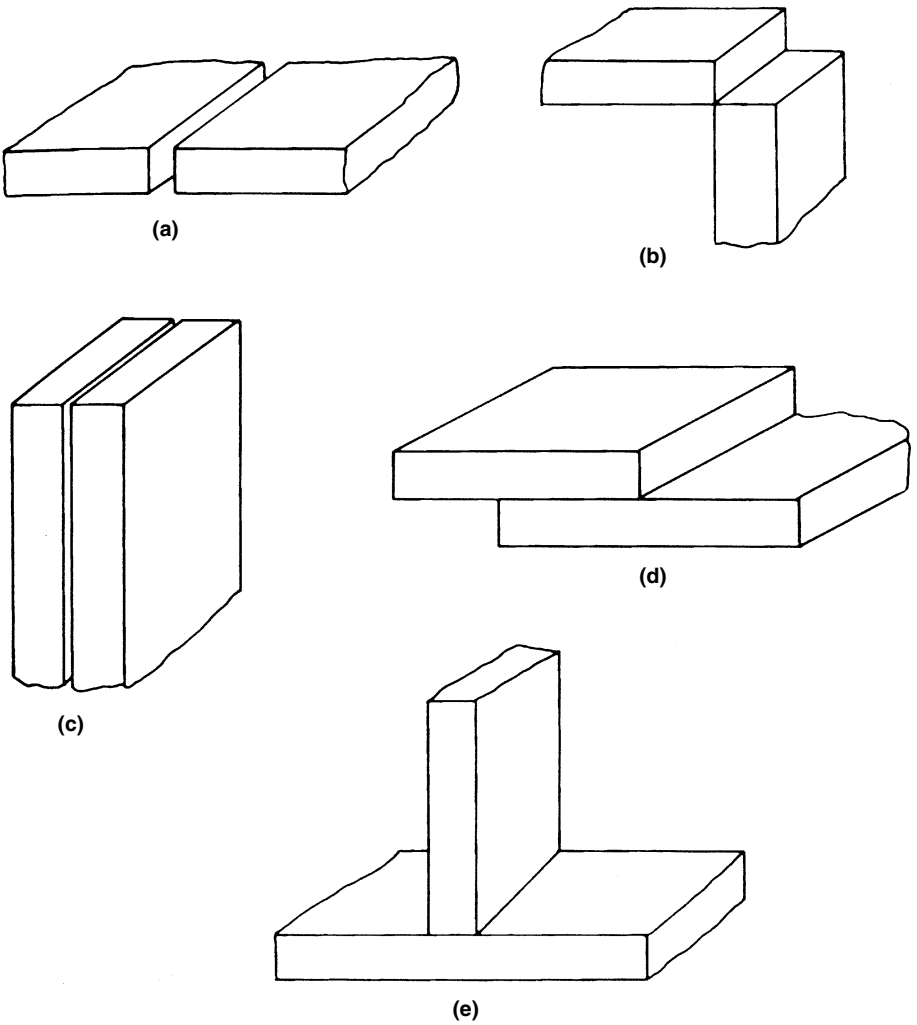

Figure 6.35 Schematic illustration of the five basic joint designs used in welding, including: (a) butt joint, (b) corner joint, (c) edge joint, (d) lap joint, and (e) tee joint. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Figure 6.31, page 229, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

Briefly, the square groove is simple to prepare, is economical to use, and provides satisfactory strength, but it is limited by joint thickness. For thick section joints, the edge of each member of the joint must be prepared to a particular geometry to provide accessibility for welding and to ensure the desired weld soundness and strength. For economy, the opening or gap at the root of the joint and the included angle of the groove should be selected to require the least weld metal necessary to give access and meet strength requirements. J and U groove preparations minimize weld metal requirements compared to Vs but add to the preparation costs. Single-bevel and J-groove

welds are more difficult to weld than V or U groove welds because one edge of the groove is vertical.

Again, the interested reader is referred to the *AWS Handbook* for more specific and detailed information.

SUMMARY

Welding is an extraordinarily effective and versatile process for joining similar types of materials, including metals and their alloys, thermoplastic polymers, glasses, some ceramics, and even composites with these materials as their matrix phase. It uses a combination of heat and pressure to bring atoms (of metals and glasses), ions (of ceramics or glasses), or molecules (of thermoplastic polymers) to their equilibrium spacing to allow atomic-level bond formation like those in the parent materials to form joints and produce joint strength. Welding of real materials (as opposed to "ideal" materials) is complicated by the existence of adsorbed layers of atmospheric gases, moisture, oxides or other tarnish compounds, and other contaminants on surfaces, as well as the fact that roughness on the atomic scale severely limits the number and total area of effective contacts needed to allow bonds to form. The challenge in practical welding is to overcome surface contaminants by cleaning and overcome surface asperities by causing melting or solid-state plastic deformation. In fact, welding processes are broadly classified as fusion or non-fusion types, depending on whether melting or plastic deformation is the principal means for bringing atoms, ions, or molecules together to effect a weld. Other classification schemes consider whether or not the process requires pressure (in pressure versus non-pressure processes), while still others consider the source of energy to cause the needed bonding (e.g., chemical, electrical, or mechanical). Subclassification of fusion welding processes considers whether or not filler is required (i.e., is autogenous) and, if it is, whether that filler is homogeneous or heterogeneous with respect to the base materials. If the process is an electric arc welding process, subclassification depends on whether the electrodes used to create the arc to the workpiece are consumable or nonconsumable (by intent), and on whether they are continuous or discontinuous if they are consumable.

The most common gas welding process (e.g., oxyacetylene), electric arc welding processes (e.g., gas–tungsten arc, plasma arc, gas–metal arc, shielded metal arc, flux-cored arc, submerged arc, electrogas, and electroslag), high-energy-density beam welding processes (e.g., electron beam and laser beam), and resistance welding processes (e.g., resistance spot, resistance seam, projection, flash, upset, and percussion) were described, along with non-fusion pressure, friction, and diffusion processes. For fusion welding processes, several potential sources for loss of energy between the source and the workpiece result in an energy transfer efficiency for these processes that varies widely based on the process but is always less than 100%.

Finally, the design of a weld joint or the joint type was described as being dependent on the geometric requirements and restraints of the structure being welded, as well as on the expected loading. Specific preparations of joint types depend on the process, loading, and cost constraints.

QUESTIONS AND PROBLEMS

1. Using the broadest, most generic definition of *welding,* which of the following joints could, at least in theory, be welded, and what specific type of bonding (primary metallic, ionic, covalent, or mixed ionic–covalent, or secondary of any kind) would create the joint?
   a. Commercially pure (CP) titanium (Ti) to CP Ti
   b. Ti–6Al–4V to Ti–6Al–6V–2Sn
   c. AISI 304 austenitic stainless steel to AISI 1045 mild steel
   d. Essentially pure aluminum, AA1100, to AISI 304 austenitic stainless steel
   e. Aluminum bronze to gray cast iron
   f. Commercially pure Ti to monolithic graphite (Tough one!)
   g. Alumina (Al_2O_3) to pure aluminum, AA1100 (Tough one!)
   h. Thermoplastic nylon 6,6 to nylon 6,6
   i. Two different silicate glasses with similar coefficients of thermal expansion
   j. Alumina (Al_2O_3) to alumina
   k. Alumina (Al_2O_3) to ZrC
   l. ZrN to ZrB2
   m. Graphite fiber-reinforced thermoplastic polyetheretherketone (PEEK) to unreinforced PEEK
   n. SiC-partical reinforced aluminum alloy AA6061 to unreinforced AA6061
   o. Portland cement to Portland cement (Tough one!)
2. If welding (by its broadest definition) is not possible for some material combinations in Question #1, how else might those materials be metallurgically or chemically joined?
3. From a fundamental standpoint, what is required to achieve chemical bonding to produce a weld and what are the practical problems encountered in making real welds?
4. If two pieces of pure aluminum were brought together such that every pair of atoms across the interface formed a bond, the resulting joint strength would be equal to the theoretical cohesive strength of aluminum. Calculate this strength (i.e., force per unit area) if the binding strength for aluminum is 3.4 eV/atom. How does this calculated strength compared to the listed fracture or ultimate strength for pure Al? [Hint: start with the equation for the binding energy, Uo, and derive the expression for force, knowing

$$U_o = A/r_o^3 + B/r_o^{12} \text{ and } F_o = -dU_o/dr_o$$

   and given that $r_o = 2.86$ Angstrom (where 1 Angstrom $= 10^{-9}$m)
5. What are some of the particular advantages of welding versus (a) mechanical fastening, (b) adhesive bonding, and (c) brazing or soldering? What is potentially the greatest disadvantage?
6. Indicate whether you think the following base material combinations would best be welded using predominantly heat or pressure, and state why.

a. Pure aluminum (AA1100) to AA1100
b. Pure ETP) copper to ETP copper
c. Pure tungsten (W) to pure W (Be careful!)
d. Gray cast iron to gray cast iron
e. Commercially pure (CP) titanium (Ti) to CP Ti (Hint: Ti's oxide dissolves in the base metal at around 1000°C or 1800°F.)
f. Alumina (Al_2O_3) to alumina
g. Soda lime glass ($74SiO_2 - 16Na_2O - 5CaO - 4MgO - 1Al_2O_3$, in wt.%) to soda lime glass
h. Thermoplastic polyvinyl chloride (PVC) to PVC
i. SiC-particle reinforced aluminum alloy AA6061 to unreinforced AA6061
j. Graphite fiber-reinforced thermoplastic polyetheretherketone (PEEK) to unreinforced PEEK

7. Sketch and label all of the microstructural zones you would expect to find for a fusion weld made between a piece of annealed pure copper and a piece of heavily cold-worked 70Cu–30Zn yellow brass. Show the relative sizes (i.e., widths) of the various zones in each piece.
8. If propane (C_3H_8) were used instead of acetylene (C_2H_2) as the fuel gas in oxyfuel welding, what would the properly balanced primary and secondary combustion reactions be?
9. Explain how an oxyacetylene welding flame should be adjusted for welding (a) an aluminum alloy; (b) a high carbon steel; (c) a 60Cu–40Zn brass; (d) a piece of 18Cr–8Ni austenitic stainless steel (with 0.08%C); and (e) a piece of used, oil-infiltrated gray cast iron (This is a tough one!).
10. What is (are) the specific advantage(s) of welding in each of the following situations and why? [Hint: there may be multiple advantages.]
    a. A submarine hull made from thick-section high-strength HY-110 steel.
    b. An all EB welded T1–6Al–4V structural box (mounted through and to the fuselage) to support the wings of a fighter airplane. [Hint: consider safety of flight and structural efficiency.]
    c. Erecting an all-aluminum alloy (say, AA6063) bridge from extruded truss elements.
    d. Repairing a cracked gray cast-iron frame of a very large forging press.
    e. Repairing damaged large-diameter pipes in the core of a nuclear reaction.
11. What are three different approaches that could be employed to help ensure that the tungsten electrode in a GTAW torch does not melt or overheat to the point that pieces of tungsten come off to contaminate the weld during DCRP operation? Explain why each would work. What could be the consequences of any W inclusions?
12. Which operating mode (DCSP, DCRP, or AC) and shielding gas (pure Ar, pure He, or a mixture of the two) would you choose to gas–tungsten arc weld each of the following applications?
    a. Single-pass, full-penetration weld in 2-mm-thick Ti–6Al–4V.
    b. Single-pass, full-penetration weld in 5-mm-thick A354 aluminum casting.
    c. Single-pass, full-penetration weld in 0.3-mm-thick AISI 304 stainless steel.

d. Single-pass, full-penetration weld in 1.5-mm-thick pure copper. (Be careful!)
e. Single-pass, full-penetration weld in 2-mm-thick AA5052 aluminum.

13. Between GTAW and PAW, which would you recommend for each of the following situations and why?
    a. Welding critical aircraft gas turbine disks made from Ni-base superalloy.
    b. Welding aircraft hydraulic line fittings to 0.50″-diameter, 0.050″-thick wall tubing made from Ti–5Al–2.5Sn.
    c. Repairing small cracks in H14 (0.40C, 5.00Cr, 5.00W) air-hardening tool steel hot forming dies.
    d. Welding 0.4-mm-thick AISI 304 stainless steel bellows for a vacuum system.
    e. Single-pass, full-penetration welding of 15-mm-thick Ti–6Al–4V.
    (Hint: think about both technical requirements and cost.)
14. Give at least five functions of the coating of a SMAW electrode. If such an electrode is to be capable of operating using AC, including geographic locations where the line voltage may drop below the nominal 110-120 volts to around 95 volts, which of these functions must be addressed and why? If such an electrode is to be used for applying hardfacing over a large surface, which function(s) must be addressed and why?
15. What is it about the FCAW process that limits what can be achieved with the flux in the core of a tubular wire? Give some examples.
16. Which molten metal transfer operating mode would you recommend for GMA welding in each of the following situations, and why?
    a. Relatively small (1/4″) fillet welds overhead.
    b. Thick section single V-groove welds down-hand.
    c. Horizontal and vertical seam welds in a vertical plane.
    d. Down-hand welds in a particularly heat-sensitive alloy.
    e. Seam welds in the drum of a large (400-lb. capacity) commercial washing machine where finished welds must absolutely not snag fragile garments.
17. How are the SAW and ESW processes similar? How do they differ? Which process would you choose for welding a protective alloy overlay onto a large-diameter (2 m) cast-iron roll? Why? Which process would you choose for welding thick hull plate on ships in a shipyard? Why?
18. Differentiate between the ‘‘melt-in’’ and ‘‘keyhole’’ modes of fusion welding. Which three common processes are capable of making welds in either mode? For what situations would you choose each more for a particular process?
19. Between EBW and LBW, which would you choose for each of the following, and why?
    a. Welding highly reactive zirconium (Zr) alloy tubes for nuclear reactor applications.
    b. Welding very thin (0.5 mm) iridium (Ir) alloys for a one-of-a-kind application.
    c. Welding very thick-section (3″) AA5083 aluminum for cryogenic tanks.
    d. Welding very thick (40 mm) AISI 305 austenitic stainless steel.
    e. Welding thick-section (1.01.5″) mild steel structure in shipbuilding. (Hint: you need to be creative to deal with the harsh environment of a shipyard!)

20. Describe how a resistance spot weld is made. What is the complete role of the forging cycle within the overall welding schedule? As the forging pressure is increased, what happens to the contact resistance? Are there and disadvantages of such a high forging pressure? If so, what are they? If not, why not?
21. The first spot weld is made in a single-overlap joint between two pieces of 1.2 mm thick automobile body stock (AISI 1020 steel). The very next spot (and every one after that) is found to be smaller in size and weaker than the very first spot weld when it was tested in tensile shear, even though the welding current, voltage, time, and pressure were identical. What happened? How can all welds be made the same in size and strength? (Hint: think of the electrical circuit and Ohm's Law!)
22. While non-fusion welding processes generally do not use an electrical energy source, they could, couldn't they? Explain why an electrical source is usually not used to accomplish non-fusion welding.
23. Explain how recrystallization and grain growth facilitate the formation of a sound weld in certain non-fusion welding processes.
24. Revisit Problem #1 and indicate for which combinations it might be possible to use a non-fusion welding process rather than a fusion welding process.
25. What are some of the restrictions of forming friction welds using rotational versus translational motion? Are all these problems overcome simply by using translational motion? If not, why not? If so, why?
26. Considering the diffusion welding of the following material combinations, how easy would it be to produce welds in each case? Explain your answer in each case.
    a. Pure aluminum (AA1100) to aluminum alloy AA6061
    b. Ti–6Al–4V to Ti–6Al–6V–2Sn
    c. Ni-base Alloy 625 to Alloy 625
    d. AISI 304 austenitic stainless steel to AISI 304
    e. Alumina (Al_2O_3) to alumina
    f. Pure aluminum (AA1100) to alumina (Al_2O_3)
    g. Pure molybdenum (Mo) to pure Mo
    h. Pure lead (Pb) to pure Pb
27. What makes non-fusion welding processes particularly attractive for joining ceramics? Among the four major mechanisms employed, i.e., (1) pressure, (2) friction, (3) diffusion, and (4) solid-state deposition (per Granjon's approach using vapor/solid reactions), which is (are) most suited to ceramics and why?
28. What is it about roll welding that tends to result in a higher-quality weld than does hot press or forge welding? (Hint: think about the motion and deformation in the vicinity of the interface in each situation.)
29. Be creative and think of several ways in which friction stir welding could be employed to weld otherwise difficult-to-weld combinations of (a) materials and (b) shapes. (Hint: what about dissimilar material types or arrangements, as in laminated composites?)
30. In what different ways could intermediate materials be used to facilitate diffusion welding under each of the following conditions?
    a. Material pieces that do not fit together well.
    b. Materials that are inherently hard.

c. To reduce the power or energy needed to make the weld.
d. To accelerate the rate of weld formation.

Bonus Problems:

A. We know it is possible to bond two like thermoplastic polymers (e.g., polyvinyl chloride) together simply by applying a suitable solvent, like acetone, to each piece, causing some softening, and pressing the two pieces together until the solvent evaporates. Explain how this process, called "solvent cementing," is more like a fusion or a non-fusion welding process than a normal adhesive-bonding process.

B. To join a metal to a ceramic, one trick is to metallize the surface of the ceramic and then braze (or solder) the metal to the metallized layer. Given that the metallized layer adheres sufficiently well that failure of the assembly often occurs totally within the ceramic, rather than at the interface between the ceramic and the metal, how is this possible? Explain how metal can be caused to form strong bonds with the ceramic during metallization but not during conventional welding. (This is a tough one!)

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Chapter 7

Brazing: A Subclassification of Welding

7.1 INTRODUCTION TO THE PROCESS OF BRAZING

It is often desirable to produce a permanent, mechanically acceptable, structurally sound, and leaktight joint without melting the base material. This could be because melting produces an unacceptable cast (versus wrought[1]) microstructure or is impossible or impractical due to an exceptionally high melting point or some other undesirable event that occurs upon melting.[2] While non-fusion welding processes are an option, there are practical limitations as to what can be joined based on shape, size, joint area, material type, and, especially, combinations and part fitup, to name a few (see Chapter 6, Subsection 6.5.1). Adhesive bonding is an option suited to the same kinds of joint shapes, sizes, areas, diverse and dissimilar material combinations, etc., but joint strength (particularly in peel) and operating conditions (especially elevated temperatures), as well as susceptibility to environmental degradation, can be serious practical limitations. The process of brazing offers a viable option.

Unlike in solid phase joining by non-fusion welding, where the joint is made by causing atomic bonding across the two faying surfaces directly (without filler and without requiring melting of the substrates), in brazing and its sister process of soldering, a liquid is created in or made to flow into and fill the space between the joint faces and then solidify. The liquid used as the filler has a lower melting point than the materials being joined, so there is no melting of the base material substrates. Brazing and soldering are distinguished from one another primarily on the basis of the melting temperatures of their respective fillers, with braze fillers melting over 450°C (840°F) and solder fillers or solders melting below this temperature. Brazing produces a stronger joint than soldering primarily because of the inherently higher melting temperature and generally stronger fillers employed. Brazed joints operate at lower hom-

[1] A *wrought* microstructure is one that has been developed by plastically working an originally cast microstructure, ridding that structure of all or most remnants of the original dendritic structure and most, if not all, solidification-induced segregation, using multiple recrystallization anneals.

[2] Some materials (notably certain ceramics) will sublime rather than melt, or decompose upon melting into a different material (e.g., $CaCO_3$ does not melt as $CaCO_3$; it transforms into CaO and CO_2 gas, and the CaO eventually melts).

ologous temperatures[3] than soldered joints and there are often greater degrees of interdiffusion between filler and substrate(s) that contribute to metallurgical bonding. For these reasons, brazing has become an extremely important and versatile method for joining commonplace as well as high-performance structures, from automobile radiator cores to aerospace honeycomb sandwich cores. By precluding the need for melting the base materials, yet producing mechanically strong, environmentally durable joints, brazing offers an extremely attractive joining option.

Figures 7.1 and 7.2 show two important applications of the brazing process in modern manufacturing (i.e., aircraft engines and automobile heat exchanger cores).

This chapter looks at the process of brazing in detail. First, the process is fully defined as a subclassification or subcategory of the broader process of welding, and as distinct from the metallurgically indistinguishable process of soldering. Then, the relative advantages and disadvantages of brazing are identified. Next, a detailed description is given of the principles of operation of the general process, as well as of some specific process embodiments for both manual or automated operation. This description is followed by a description of brazing filler materials, their basic

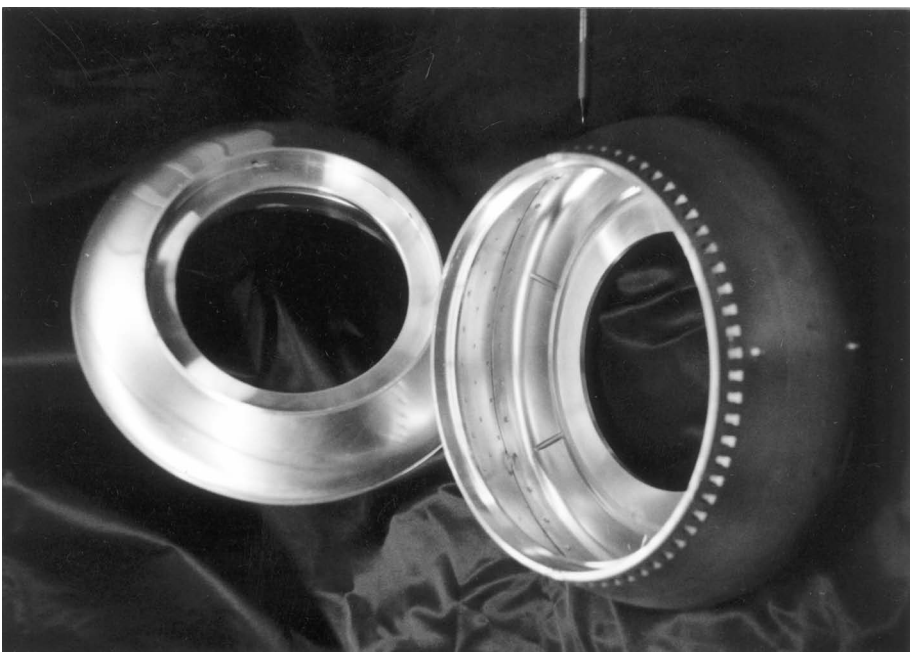

Figure 7.1 Typical brazed assemblies; here, inlet ducts for the ''Huey'' helicopter's gas turbine engine. (Courtesy of Modern Metal Processing, Inc., Williamston, MI, with permission.)

[3] Recall that *homologous temperature* refers to the ratio of actual temperature to the melting point of a material on an absolute temperature scale such as degrees Kelvin (°K, analogous to °C), or degrees Rankine, (°R, analogous to °F).

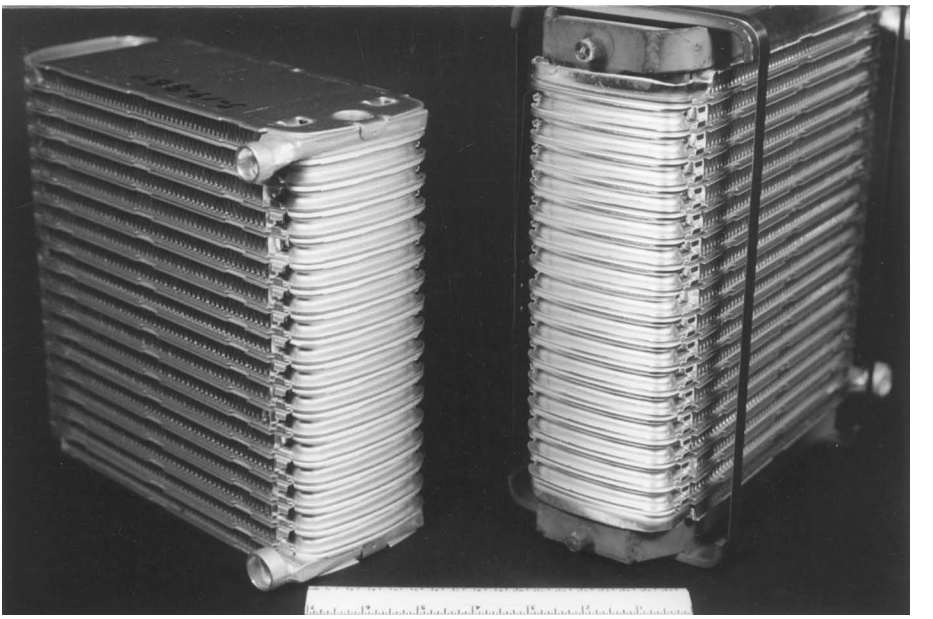

Figure 7.2 Typical vacuum brazed assemblies; here, evaporators used in automobile climate-control systems. (Courtesy of Modern Metal Processing, Inc., Williamston, MI, with permission.)

characteristics, their general physical metallurgy, and their most important types within a widely accepted classification scheme. The critically important role of fluxes and/or atmospheres for providing a clean wettable surface for brazing is then described. Finally, a brief description of joint designs and general joint properties is given.

7.2 BRAZING AS A SUBCLASSIFICATION OF WELDING

7.2.1 General Description of the Relationship Between Brazing and Welding

Brazing is a subcategory or subclassification of welding that warrants distinction because it produces coalescence of materials by heating those materials to a suitable temperature to cause a filler material having a liquidus temperature above 450°C (840°F)—some sources say 425°C (800°F), while other, much older sources say 538°C (1,000°F)—and below the solidus temperature of any base materials involved. Only the filler material melts, allowing that filler to solidify to produce joint strength. The filler material, or *filler*, is necessarily of a different composition than the base materials and is distributed between close-fitting surfaces of the joint by surface wetting, interdiffusion and possibly chemical reaction, and spreading. Capillary

action plays a major role in filler flow through the joint, while surface wetting plays a major role in the filler's spreading. Chemical bonds are formed between the filler material and the base materials, and substantial diffusion of elements in the filler into the base material, and vice versa, almost always occurs. Braze fillers can be metallic, for joining metals or ceramics to themselves or to one another, or they can be ceramics for joining ceramics to ceramics. Atomic-level bonding is almost always primary, and can be metallic, ionic, covalent, or mixed ionic–covalent depending on the specific natures of the filler and the base materials.

So, to be a true brazing process, *all* of the following criteria must be met: (1) joint elements must be joined without melting the base materials involved; (2) a filler must be used; (3) the filler material must have a liquidus temperature above 450°C (840°F); (4) the filler material must wet the base material surfaces; and (5) the filler must be drawn into or held in the joint by capillary action, depending on whether the filler is added during brazing or preplaced prior to brazing. Brazing is arbitrarily distinguished from soldering by the filler material's melting temperature. In soldering, the filler materials melt below 450°C (840°F). A process called "braze welding" is not, in fact, a true brazing process, even though base material melting is not involved (but a melting filler is). In braze welding, a filler metal is deposited in a prepared groove or fillet exactly at the point where it is to be used, and spreading by surface tension or capillary action is not a factor. Limited base metal fusion may also occur. This process is discussed in Chapter 10, Section 10.3.

To achieve a good finished joint using any of the various specific brazing processes, the following four basic elements must be considered: (1) joint design, (2) filler material, (3) joint heating, and (4) protective or reactive shielding. Briefly, the joint design must afford a suitable capillary for the molten filler material when joint elements are properly aligned. The need is to enable filler flow and assure coverage. Filler material must melt at a lower temperature than the base material(s), to allow flow, substrate wetting, and interdiffusion. This means at least some component of the filler must be soluble in the substrate solvent or vice versa.[4] To allow brazing, heat can be applied locally at the joint or to the entire assembly to be brazed. In either case, a temperature must be reached at the joint to allow the filler to melt, wet, and flow, and temperature must be uniform (at least in the joint proper) to prevent uneven or incomplete filling. Protective shielding is required during brazing to prevent oxidation of cleaned joint faying surfaces during heating and until braze flow is completed. This can be accomplished with either a chemical flux or an inert atmosphere. Sometimes a reactive flux or atmosphere is required to actually clean and chemically activate the surfaces to be brazed.

Figure 7.3 schematically illustrates some of the key differences between brazing and fusion welding.

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[4] As an alternative to interdiffusion to cause mass transfer to facilitate bonding, it is also possible for some component in the filler to simply chemically react with some component in the substrate, often producing an intermetallic layer, as occurs in "reactive brazing."

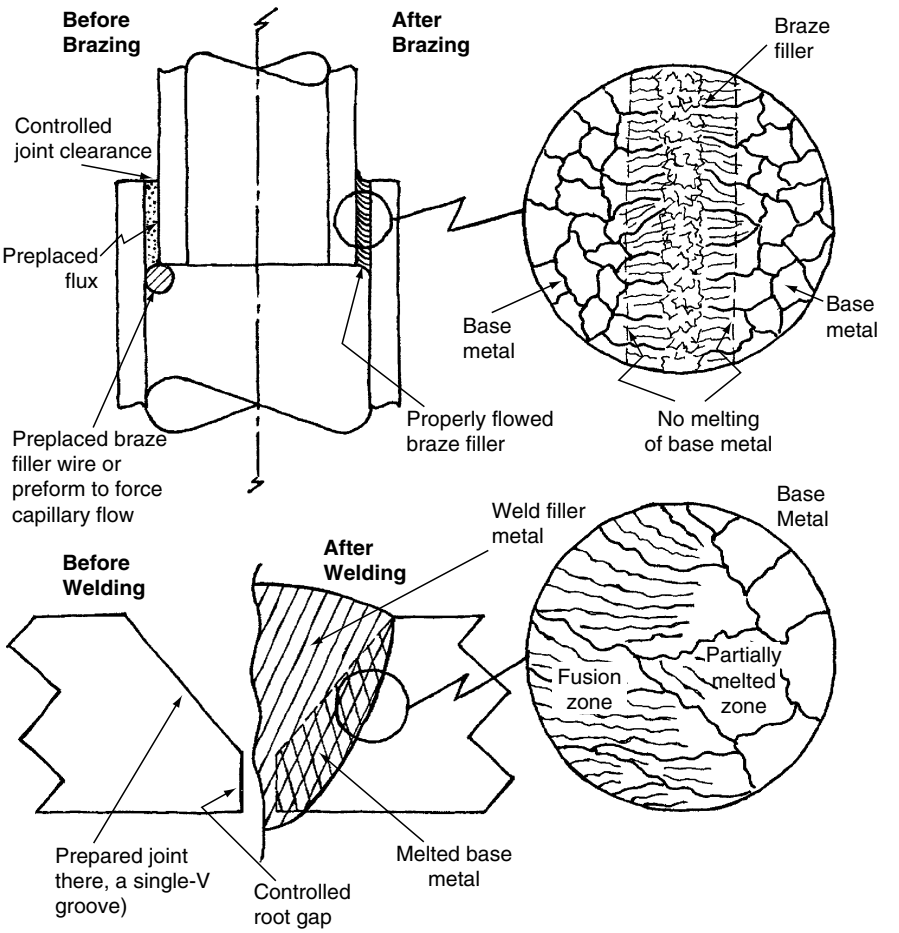

Figure 7.3 Schematic illustrations showing some of the key differences between brazing (top) and fusion welding (bottom), before and after joint creation, including a schematic representation of the resulting microstructure in the joint.

7.2.2 Advantages and Disadvantages of Brazing

Like all joining processes, brazing offers certain advantages but also has certain limitations and shortcomings. Perhaps the most important advantage is that brazing has little or no effect on the composition of the base material(s), thereby preserving special base material characteristics where these are critical or desired. In brazing there is no melting of the substrate and, thus, no gross mixing between filler and base material(s). There may be, and often is, some interdiffusion, but this usually does

not change the composition significantly, even in the immediate vicinity of the joint.[5] For some brazing processes and base materials, there is also very little heat effect on the substrate either, since heating is either relatively low compared to the melting temperature of the substrate(s) and/or heating is highly localized. Since brazing temperature can be kept relatively low compared to the substrates' melting temperatures, the process can be the ideal choice where base material melting cannot or should not occur. For other brazing processes, the entire structure or assembly to be brazed is raised to the brazing temperature, so heat effects can be significant if the brazing temperature is high relative to the melting temperature of the substrates, but any such effects will be uniform throughout the structure or assembly.

Related to these process characteristics is the fact that brazing is often an ideal choice for joining dissimilar material types, not just compositions. Provided that filler can be found that wets all of the substrate materials involved in the joint assembly, sound joints can usually be made. Limited intermixing again contributes to this important processing advantage.

The brazing process has the ability to join cast, wrought, or powder-processed (including intentionally porous) metals, dissimilar metals, oxide and non-oxide ceramics, metals to ceramics, carbonaceous materials (e.g., graphite), and fiber- or dispersion-strengthened composites with metallic, ceramic, intermetalllic, or carbonaceous matrices. It provides a simple means for bonding large joint areas or long joint lengths. The surface bonding action of the thin braze layer in lap-type joints (as with adhesive bonding) results in excellent stress distribution. Like in adhesive bonding (Chapter 4), the uniform distribution of stress over large areas allows the joining of very thin sections, as well as the joining of thick to thin sections. The only drawback in this regard is that there can be a pronounced notch effect due to the thinness of the joint if loading is in tension (i.e., there will be little strain compliance). The process also allows the affordable fabrication of complex assemblies, often consisting of many components requiring many joints to be made simultaneously. Finally, brazing offers the ability to join large, complex structures under relatively stress-free conditions and is capable of producing precision tolerances reproducibly in production.

In terms of service, braze joints often have limited elevated temperature serviceability and stability because of the low melting point and strength of the filler (relative to the base materials) and the high diffusion rate of some of the filler components. With proper choice of filler and process (e.g., diffusion brazing), however, joint temperature capability can approach that of the base material.

Table 7.1 summarizes the relative advantages and disadvantages of brazing as a joining process.

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[5] An exception is "diffusion brazing," in which diffusion of one of the components from the filler into the base material is essential to the creation of the joint. The joint is either formed by what is known as "isothermal solidification" or the remelt temperature of the newly formed braze joint is required to be higher than the original melting temperature of the filler. In diffusion brazing, the composition in the vicinity of the joint is usually noticeably changed.

Table 7.1 Advantages and Disadvantages of Brazing

Advantages	*Disadvantages*
• No melting of base material(s) • Little or no effect on the composition or microstructure of base material(s) • Excellent for joining dissimilar material types and compositions within a type • Allows large area bonding, so distributes stress evenly over a large area • Allows joining of a wide variety of thicknesses, especially thin-to-thin and thin-to-thick • Allows joining of porous materials (e.g., powder-processed parts) • Provides affordable fabrication of complex, multicomponent assemblies • Allows simultaneous production of joints en masse • Gives rise to very low distortion and/or residual stresses, if CTEs are matched • Easy to automate, suitable for batch or continuous processing	• May exhibit limited elevated temperature service and stability • Can exhibit a pronounced notch effect due to the thinness of the braze layer, often exacerbated by an intermetallic reaction layer • Requires fluxing or atmosphere control and removal of flux residue • Requires use of parts arranged with controlled gaps or clearance at joints • Challenges inspection; demands NDE

7.3 PRINCIPLES OF BRAZE PROCESS OPERATION

Capillary flow is the dominant physical principle that ensures good brazements.[6] Capillary flow is the result of a liquid lowering the surface free energy of a solid–vapor interface by wetting that solid in accordance with Young's equation,[7] which is:

$$\gamma_{vs} = \gamma_{ls} + \gamma_{vl} \cos \theta \tag{7.1}$$

where γ_{vs}, γ_{ls}, and γ_{vl} are the surface free energies for the vapor-solid, liquid-solid, and vapor–liquid interfaces, respectively, and θ is the angle of contact or "wetting angle" for the liquid on the solid. Capillary flow is facilitated by low angles of θ, (i.e., good wetting). In actual practice, brazing filler-material flow characteristics are also influenced by dynamic considerations involving the molten filler's fluidity or viscosity and vapor pressure, gravity, and, especially, the effects of any chemical or metallurgical reactions between the filler and the base material(s).

[6] A *brazement*, like a *weldment*, refers to the assembly being joined or already joined by brazing, as opposed to welding.

[7] Other similar relationships can appear in Young's equation, as when a flux is used and the surface energy of the molten braze–substrate interface must be lower than that of the molten flux–substrate interface for the braze to displace the flux.

In general, the brazed joint is one of relatively large area and very small thickness, and the process of brazing is predominantly controlled by surface conditions. In the simplest application of the brazing process, four critical steps are involved. First, the surfaces to be joined must be cleaned to remove all contaminants, including oxide or tarnish layers on metallic substrates. Second, in brazing metals and alloys, the surfaces must be coated with a material called a "flux," capable of dissolving solid metal oxides or other tarnish compounds (e.g., sulfides, carbonates) still present and preventing re-oxidation. Third, the joint area must be heated until the flux melts and cleans the base materials through its chemical reactivity; the flux then protects the cleaned substrate against further oxidation by remaining as a layer of liquid flux. Fourth, the brazing material must be melted at some point on the surface of the joint, displacing any flux through the combination of its higher density and its lowering of the surface free energy compared to the flux–substrate interface (as mentioned in footnote 6), and wetting and spreading throughout the joint to effect the formation of the chemical bonds. Instead of fluxes, brazing is sometimes performed with an active gaseous atmosphere, such as hydrogen, for parts needing cleaning, or an atmosphere of inert gas or vacuum for parts that are already clean. When atmospheres are used, the need for post-braze cleaning of the potentially corrosive and usually hydroscopic flux residues is eliminated.

Joints to be brazed are usually made with relatively small clearances between lapped joint elements, typically 0.025–0.25 mm (0.001–0.010 in.). High fluidity of the molten filler is thus an important characteristic. Joint assembly for proper positioning, alignment, and fitup (or gapping) usually requires tooling or fixturing, which includes some means of ensuring the proper gap (e.g., shims). Shrinkage stresses arising from the volume change of the filler as it solidifies and from thermal contraction are usually low compared to fusion welding, so brazed joints are made in a relatively stress-free condition.

In summary, brazing is an economically attractive process for the production of high-strength, metallurgical-quality bonds, while preserving desired base material properties and achieving precision tolerances.

7.4 BRAZING PROCESSES

7.4.1 General Description of Brazing Processes

Brazing processes are customarily designated according to the source or method of heating, not unlike welding processes. Manual processes are possible but automated processes predominate, mostly because so much of the formation of sound joints is the result of the naturally occurring, capillary force–driven process. Some processes restrict heating to the joint proper (especially if only one joint needs to be brazed), while others uniformly heat the entire assembly of parts making up the brazement. The methods currently of most industrial significance, and described in detail in the following subsections, are torch brazing, furnace brazing, induction brazing, resistance brazing, dip brazing, infrared brazing, and diffusion brazing. Several specialized brazing processes

Table 7.2 Classification of Brazing Processes by Energy Source

Chemical Heat Sources
Torch Brazing (TB)*
(Gas) Furnace Brazing (FB)**
Exothermic Brazing (via SHS or CS)*
Vapor-Phase Brazing (VPB)**
Electrical Heat Sources
(Electric) Furnace Brazing**
Chemical Dip Brazing (DB)**
Molten Metal Dip Brazing (DB)**
Induction Brazing (IB)*
Infrared Brazing (IRB)*
Diffusion Brazing (DFB)
- Reaction Brazing**
- Transient Liquid-Phase Bonding (TLPB)**
Resistance (Blanket) Brazing (RB)**
Laser Beam Brazing (LBB)*
Electron Beam Brazing (EBB)*

*Localized heating of the joint
**Generalized heating of the entire assembly

are also worth noting, including laser brazing, electron beam brazing, microwave brazing, ultrasonic brazing, combustion synthesis or exothermic brazing, vapor-phase brazing, and step-brazing. Braze welding, although often considered a brazing process, is actually a variant of welding or brazing, as discussed in Chapter 10, Section 10.3. All of the aforementioned processes can be performed by localized heating, except the processes that employ furnace heating, dipping into a molten metal bath, diffusion between filler and substrate(s), or vapor-phase condensation as the source of heating.

Table 7.2 gives a classification of brazing processes.

7.4.2 Torch Brazing

Torch brazing (TB) is accomplished by heating the joint area locally with one or more oxy-fuel gas torches a typical example is shown in Figure 7.4. Depending on the temperature (depending on the filler to be melted) and amount of heat required (related to the thermal mass to be heated), the fuel gas can be, among others, natural gas, MAPP gas, propane, or acetylene burned with air, compressed air, or pressurized oxygen. Torches for accomplishing brazing are identical to those used for oxy-fuel gas welding (see Figure 6.10) and can be used manually or automatically (i.e., in machine operation). Single or multiple flame tips are available, with the multiple tips being employed for larger, heavier brazements. During torch brazing, filler may be preplaced at the joint in the form of rings (e.g., for tubular assemblies), washers, strips, slugs, shims, powder, or special shapes (i.e., preforms) or may be fed from hand-held wire or rod. Fluxes should always be used.

Figure 7.4 A typical application of manual torch brazing; here, oxy-fuel gas-torch brazing of a fitting onto a hydraulic line for an aircraft engine. (Courtesy of The General Electric Company's Aircraft Division, Evansdale, OH, with permission.)

7.4.3 Furnace Brazing

Furnace brazing (FB) is used exclusively where the parts to be brazed can be assembled with the filler material preplaced in or near the joint(s). It is particularly applicable for high production numbers and rates. Preplaced filler can be in the form of wire, foil, filings, slugs, shims, powder, paste (with flux mixed in), tape, or shapes (i.e., preforms). Fluxing is used except when an atmosphere is specifically introduced into the furnace to perform the same shielding and/or reducing function it does in fusion welding. Hydrogen and either exothermic or endothermic combusted gases are usually used for reduction, while inert gas (e.g., usually argon) is used for protecting reactive metals from oxidation. Vacuum atmospheres on the order of 10^{-2}–10^{-5} atmospheres (or low) are also widely used, especially in aerospace, and often preclude the need for and use of flux, whose residue must be totally removed by post-braze cleaning to avoid later corrosion. Vacuum brazing cannot be performed with certain high vapor-pressure fillers or base materials, however. Furnaces are either batch or continuous types, are heated by electrical resistance elements or gas or oil flames, and should have automatic time and temperature and, possibly, atmosphere controls. Cooling chambers or forced atmosphere injection cooling is often used to speed up and control solidification for metallurgical purposes and subsequent cooling of the assembly for productivity purposes. Figure 7.5 shows a typical furnace brazing operation.

7.4.4 Induction, Resistance, and Microwave Brazing

The heat necessary for brazing with the *induction brazing* (IB) process is obtained from an electric current induced in the parts to be brazed. Heating can be restricted to the

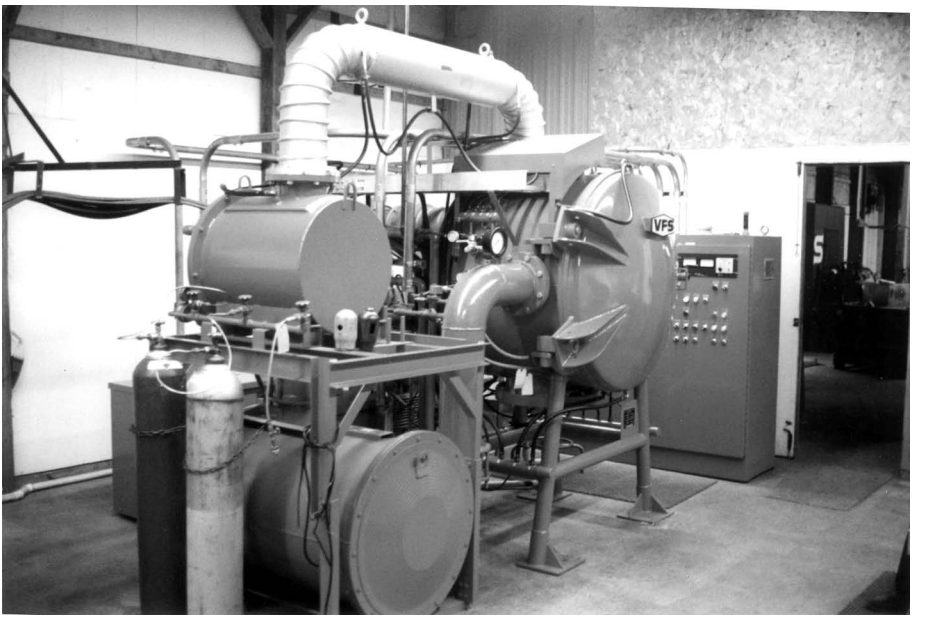

Figure 7.5 A typical furnace brazing facility, including an HC36 VFS brazing furnace. (Courtesy of Modern Metal Processing, Inc., Williamston, MI, with permission.)

immediate area to be brazed or can be more general. Typically, water-cooled coils carrying high-frequency alternating current are used by being placed in close proximity to the parts to be brazed, but not as a part of the electric circuit. Figure 7.6 illustrates some examples of induction brazing coils, the design of which involves a degree of art beyond science.

Brazing filler is usually preplaced during induction brazing, with forms being similar to those used with furnace brazing. Careful joint design and coil setup are essential to ensure that all surfaces of all members of the joint reach the brazing temperature at the same time. Otherwise, filler flow will not occur as intended. Flux is used with this process, except when an atmosphere (often a vacuum) is specifically employed.

The three common sources of high-frequency alternating electric current for performing induction brazing are (1) the motor–generator (5,000–10,000 Hz); (2) the resonant spark gap (20,000–300,000 Hz); and (3) the vacuum tube or solid-state oscillator (20,000–5,000,000 Hz). The depth of heating is determined by the frequency of the power source. Higher frequencies produce shallower heating, until finally only ''skin heating'' occurs. The rate of heating is always fairly fast for brazing and soldering processes, typically 10 seconds to 1 minute. Part thicknesses for induction brazing are generally thin, in the range of up to 3 mm (0.125 in).

A related process is *resistance brazing* (RB), where joint heating is produced by the resistance at the joint contact surfaces for current introduced through electrodes that make the brazement part of the electric circuit. Conventional resistance welding

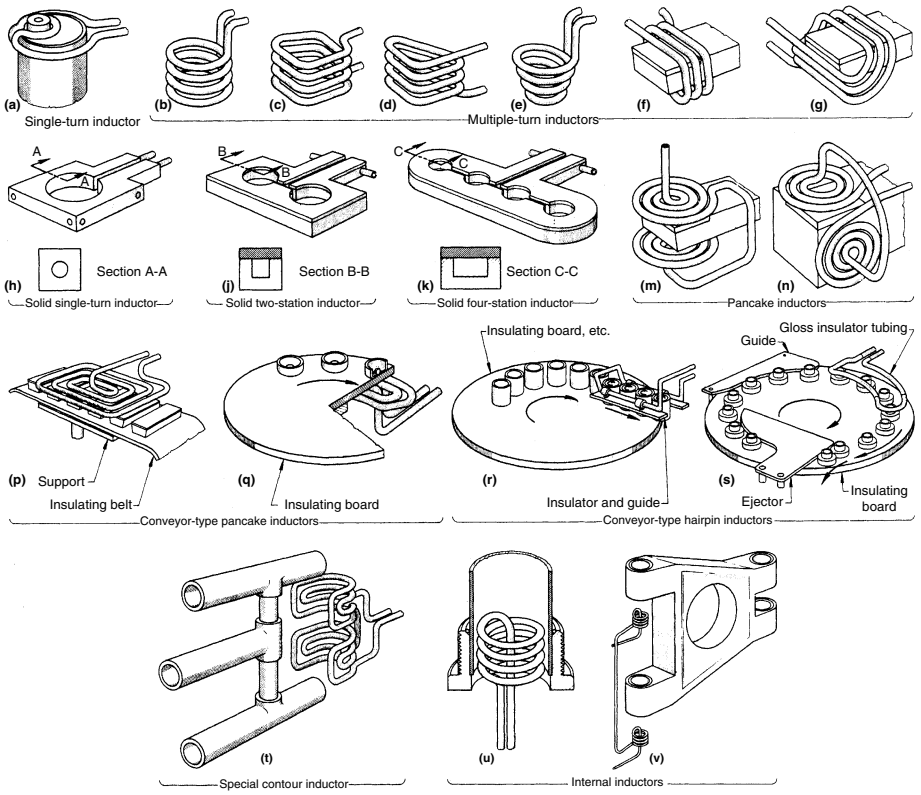

Figure 7.6 Schematic illustrations showing representative induction brazing coils and devices. (Reprinted from *Brazing Manual,* Fig. 1.6, page 5, American Welding Society, Miami, FL, 1984, with permission.)

machines are typically used, with alternating current. The particular advantage of resistance brazing is very rapid heating capability.

A specialized form of brazing also closely related to induction brazing is *microwave brazing* (MWB). While still used only for highly specialized applications (e.g., brazing TSP diamond and tungsten carbide in cutting tools), it can be very effective for what would otherwise be very difficult brazing challenges.

7.4.5 Dip Brazing

There are two methods of *dip brazing* (DB): (1) chemical bath dip brazing and (2) molten metal bath dip brazing. In *chemical bath dip brazing*, the filler, in suitable form, is preplaced in or near the joint and the assembly is immersed in a bath of molten salt. Molten salts have high specific heat capacities and high thermal conductivities, and so are excellent for furnishing the heat needed for brazing. In addition, the molten salts are usually aggressive enough to provide the necessary fluxing/cleaning action and

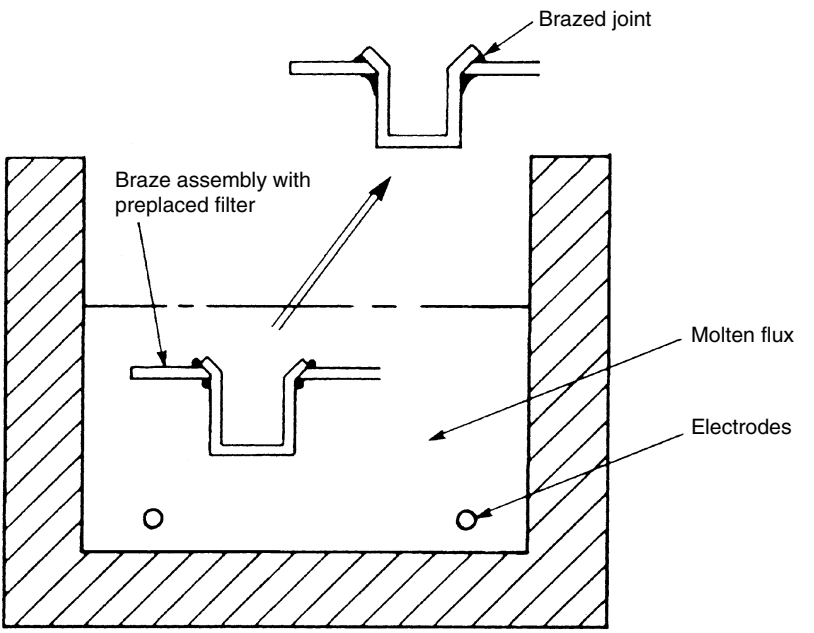

Figure 7.7 Schematic illustration of a typical dip brazing setup. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 8.3, page 291, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

oxidation protection. If not, a suitable flux may be required that would normally be floated on the surface of the denser molten salt. In *molten metal bath dip brazing*, the parts to be brazed are immersed in a bath of the molten brazing filler alloy. The parts must be first cleaned and fluxed (if necessary), and a cover of molten flux should be maintained over the molten metal bath to protect it from oxidation. Figure 7.7 schematically illustrates a typical dip brazing setup.

The dip brazing process is usually restricted to small parts and, since the entire assembly is heated to the brazing temperature and may be exposed to aggressive chemicals, the assembly must be tolerant of heating to the required temperatures, corrosive chemicals, and subsequent aggressive cleaning to remove embedded salt from the chemical bath dip process. A particular advantage of the molten metal bath dip process is that many braze joints can be made at the same time in a complex assembly, because the molten metal bath provides filler at the same time it provides heating.

7.4.6 Infrared Brazing

Infrared brazing (IRB) uses infrared (IR) heating through irradiation with long-wavelength light in the visible spectrum. High-wattage (e.g., 5,000 watt) lamps like those sometimes used to preheat welds are often used. These lamps should be placed close to the workpiece, since heat input intensity drops off as the square of the distance from

the source. It is best if the lamps follow the contour of the parts closely (to provide uniform proximity), but it is not essential. Heating can take place in air, vacuum, or under inert atmosphere. After heating, the part is moved out of the IR source, often to cooling platens.

The infrared brazing process is particularly suited to the brazing of very thin materials such as honeycomb and honeycomb sandwich panels used in aerospace applications. It is rarely used with material thicker than approximately 1.3 mm (0.05 in).

7.4.7 Diffusion Brazing and Transient Liquid-Phase Bonding

Unlike the previous brazing processes, *diffusion brazing* (DFB) is not defined by its heating source but, rather, by the mechanism involved in forming the bond at the joint. A joint is formed by holding the brazement at a suitable temperature for sufficient time to allow mutual diffusion of the base and filler metals. Rather than the filler melting and flowing, the liquid that fills the joint is produced from a reaction between the filler and the base material, producing a transient liquid phase, actually a eutectic constituent.[8] For the preceding reasons the process is also called "reaction brazing"[9] or *transient liquid phase bonding* (TLPB). Solidification occurs isothermally (i.e., without cooling) because the solidus of the new composition of the joint produced by diffusion is higher than the temperature at which the eutectic reaction initially occurred. The resulting joint ends up with a composition considerably different from either the filler or the base materials, and no filler should be discernible in the final microstructure of a properly produced joint.

The typical thickness of base materials that are diffusion brazed ranges from foil to several inches (i.e., more than 50 mm). Relatively heavy parts can be brazed using this process because the process is not sensitive to joint thickness. Many brazements can be made by DFB that are difficult or impossible to make by other brazing methods.

The diffusion brazing process produces much stronger joints than normal brazing processes, frequently approaching the strength of the base material (i.e., yielding joint efficiencies of near or over 100%). Butt and lap joints, in particular, exhibit excellent mechanical properties. Mechanical fixturing or tack welding may be required to hold parts together during brazing. Unlike diffusion welding, however, no auxiliary pressure is needed. On the other hand, DFB requires a relatively long time (1–24 hours) to complete, but many joints can usually be produced at the same time. The DFB joint also has a re-melt temperature approaching that of the lower melting base material, so service temperatures can be extended over most other brazing processes.

Figure 7.8 schematically illustrates diffusion brazing or transient liquid-phase bonding.

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[8] One should remember that a eutectic is not a phase but, rather, a microstructural constituent that consists of an intimate mechanical mixture of two (or more) phases.

[9] The problem with this name is that it is easy to confuse with "reactive brazing," which is a particular method of brazing ceramics using metallic fillers containing reactive metals (e.g., Ti or Zr).

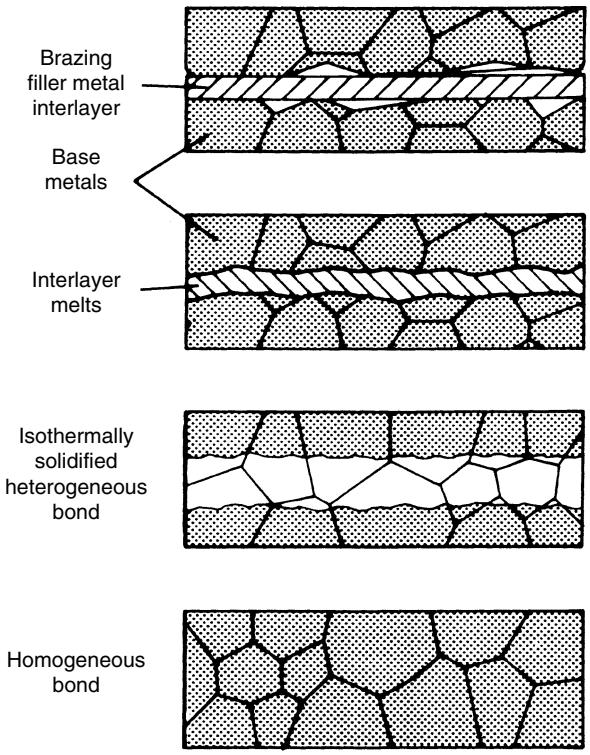

Figure 7.8 Schematic illustration of the key steps in diffusion brazing or transient liquid phase bonding to produce a homogeneous metallurgical bond at the end of the process.

7.4.8 Other Special Brazing Methods

Several other methods of brazing are used for special applications. These include blanket (resistance) brazing, exothermic brazing, laser brazing, electron beam brazing, ultrasonic brazing, vapor-phase brazing, and step-brazing. *Blanket (resistance) brazing* simply uses a resistance-heated blanket to transfer heat to the brazement by a combination of radiation and conduction. The process is good for contoured parts and/or outdoor use. *Exothermic brazing* obtains the heat for brazing from an exothermic chemical reaction, usually between solid-state reactants consisting of a powdered metal and a powdered metal oxide, with one of the better-known reactions being the aluminothermic reaction between Fe_3O_4 and Al in thermit welding. More recently, the process has tended to focus on so-called "combustion synthesis" (CS) or "self-propagating high-temperature synthesis" (SHS) reactions, which occur during the formation of oxides, carbides, silicides, aluminides, and various other ceramics and intermetallic compounds. The process is particularly useful for joining otherwise difficult-to-join combinations of refractory metals or alloys, intermetallics (or long-range-ordered alloys), ceramics, and various carbonaceous materials (e.g., graphite). Reactants are preplaced in the intended joint

between joint elements, and the exothermic reaction is caused to take place therein. The heat of reaction is normally so high that some superficial melting of the substrates occurs along with the production of at least one liquid-phase product.

The *laser brazing* and *electron beam brazing* processes use beams of photons or electrons, respectively, to locally heat a joint containing preplaced braze filler in some form. The particular advantages of both processes are very rapid heating, minimal heating of the body of the brazement, and precise dimensional control. While the laser brazing process can be performed in inert atmosphere, the EB process must be performed in vacuum to allow the beam of electrons to flow unimpeded by molecules in the air.

Ultrasonic brazing (USB) really is ultrasonically assisted brazing by other, more conventional methods (e.g., dip brazing). The ultrasonic vibration energy simply helps remove voids and gas pores from the molten filler and improves fill, fill integrity, and wetting.

Vapor-phase brazing and step-brazing are highly specialized processes. In *vapor-phase brazing*, vapors of metals are combined in the vapor state to form a low melting alloy that deposits on the brazement and produces a bond by being drawn into the close-fitting joints by capillary action. Copper and zinc vapors have been combined to produce brass brazing filler alloys. *Step-brazing* is really a procedure, not a process. It is used for accomplishing multiple brazed joints sequentially. By choosing braze fillers with progressively lower melting temperatures, brazes can be made near previously made joints without causing unwanted re-melting.

7.5 BRAZING FILLER MATERIALS

7.5.1 Basic Characteristics Required of Braze Fillers

For satisfactory use in brazing, filler materials must possess certain basic characteristics. First, filler materials must have the ability to form brazed joints possessing suitable mechanical, physical, and chemical properties for the intended application. This often means strength, but may also include ductility, impact toughness (especially below room temperature), electrical or thermal conductivity, temperature resistance and stability, and corrosion resistance. An extremely important physical property for intended fillers is that they have a coefficient of thermal expansion (CTE) that closely matches those the substrates being joined, or, if those substrates have drastically different CTEs from one another, the filler should have a CTE that bridges the CTEs of the two substrates. This is so that thermal mismatch stresses across the joint do not cause failure by fracture. Second, the melting point or range of an intended filler material must be appropriate to the base materials being joined and have sufficient fluidity at the brazing temperature to flow and distribute into properly prepared joints by capillary action. A "suitable" melting range means one below the solidus of the lowest-melting base material but as high as necessary to meet service operating-temperature requirements. Third, the composition of the intended filler must be sufficiently homogeneous and stable that separation of constituents, known as "liquation," does not occur under the brazing conditions to be encountered. Obviously, the

intended filler composition must also be chemically compatible with the substrates to avoid adverse reactions during brazing or by subsequent sacrificial (e.g., galvanic) corrosion. Fourth, intended fillers must have the ability to wet the surfaces of the base materials being joined to form a continuous, sound, strong bond. Fifth, depending on requirements, intended fillers must have the ability to produce or avoid reactions with the base materials. Usually, it is desirable to avoid such reactions, since brittle intermetallics may result, degrading joint tolerance of strain and toughness. However, for so-called "active-metal" or "reactive brazing," it is necessary for the filler and the substrates to react chemically in a particular way (see Chapter 12).

The characteristics of melting and fluidity, liquation, and wetting and bonding deserve special consideration and so are dealt with in more detail in the following paragraphs.

Melting and Fluidity

Pure crystalline metals and ceramics melt at a discrete temperature, and molten metals, in particular, are generally very fluid. Alloys, on the other hand, whether metallic or ceramic, melt over a range of temperatures from the solidus to the liquidus for the particular composition and can have a fluidity that varies greatly depending on the relative amounts (or fractions) of liquid and solid present at the brazing temperature. This "mushy" state always reduces the fluidity compared to the fully liquid state. The wider the mushy range (i.e., range between the liquidus and solidus temperatures), the more sluggish the flow of filler can be under the force of capillary action. Special care must therefore be taken in selecting and employing alloy fillers for brazing to ensure proper fluidity.

Most braze alloys are designed to be more complex than simple binaries, often for the purpose of altering the liquidus–solidus range and phase proportions as much as for any other property. A brazing alloy will always have a liquidus that is below the melting point of the lowest melting component of the filler alloy, and so will always be suitable for brazing a joint composed of parts of the elemental component.

Liquation

Because the compositions of the solid and liquid phases of brazing filler materials in equilibrium (or even present together under most non-equilibrium conditions) differ because of the distribution coefficient for the alloy solute, the proportion and composition of each phase will undergo gradual changes as the temperature increases from the solidus to the liquidus. If the portion that melts first is allowed to flow away from the remainder of the unmelted filler by capillary spreading, the remaining solid has a higher melting point than the original composition of the filler had. It never melts, and it remains behind as a solid "skull." This phenomenon is known as "liquation," and obviously, such separation is undesirable. The tendency for liquation should be minimized in properly designed brazing filler alloys. This is accomplished by employing filler alloys with narrow melting ranges and by heating rapidly through the melting range during brazing. Optimum brazing temperature for a particular filler alloy is

usually about 30–90°C (50–200°F) above the liquidus of the filler alloy. This "super heat" ensures flow without liquation.

Wetting and Bonding

To be effective, a brazing filler material must alloy with the surface of the base material without undesirable degrees of diffusion into the base material, dilution of the filler by the base material, base material erosion, or formation of brittle (usually intermetallic) compounds at the interface. These effects are dependent upon the solubility between at least one elemental component of the filler and the base material and vice versa, the amount of brazing filler material present, and the temperature and time profile of the brazing thermal cycle.

7.5.2 Braze Filler Selection Criteria

The following factors should be considered when selecting a brazing filler material, whether it is a metal or a ceramic. First, it should be compatible with the base material and the joint design (see Section 7.7). Compatibility with the base material means properly matching chemical, mechanical, and physical properties. Compatibility with the joint design means proper mechanical properties for the type and magnitude of loading (e.g., static versus fatigue, and tension, shear, or peel). Second, the filler material must be suitable for the planned service conditions for the brazed assembly, including service temperature (as this could cause melting in the extreme, and loss of strength at a minimum), thermal cycling (as this could lead to thermomechanical fatigue), life expectancy (as this could depend on susceptibility to fatigue or corrosion or both), stress loading (as this depends on inherent strength of the filler), corrosive conditions (as this leads to selective attack of the filler and degradation of the joint), radiation stability (as this could lead to embrittlement), and vacuum operation (as this is dependent on the vapor pressures of the various components in the filler that could lead to their selective evaporative loss, or to outgassing).

A third factor is that the filler material must be selected based on the brazing temperatures required and acceptable to the various parts of the assembly and to the production environment. Low temperatures are usually preferred for economizing on the energy needed for heating, to minimize heat effects on the base material (e.g., annealing, grain growth, warpage, etc.), and to minimize interactions (e.g., embrittlement by intermetallics or other brittle phases that form over time). On the other hand, high temperatures are preferred to take advantage of higher melting alloys for their economy, to combine stress relief or other heat treatment of the base material with the process of brazing, to promote interactions that will increase the joint's remelt temperature, or to promote the removal of certain refractory oxides in vacuum or certain atmospheres.

Finally, filler material selection depends on the method of heating to be used. Alloys with a narrow (i.e., 30–50°C (50–90°F)) melting range can be used with any heating method. Fillers with wider melting ranges that are prone to liquation should be brought to brazing temperature very quickly, so processes with more intense heating are preferable.

7.5.3 The Metallurgy of a Key Filler System (Cu–Ag)

While it is certainly not possible or appropriate in a work like this to consider the metallurgy of every possible or major brazing filler alloy to understand how these alloys behave, neither is it necessary. It is possible to understand much of the physical metallurgy of brazing filler alloys by considering the copper-silver (Cu–Ag) alloys, as this is a key alloy filler system that is fully representative of virtually every other braze (as well as solder) filler alloy. The basic metallurgy of solidification as it pertains to fusion welding, brazing, and soldering is addressed in Chapter 9.

Figure 7.9 presents the constitutional or equilibrium phase diagram for the Cu–Ag binary alloy system. This diagram is quite representative of virtually all brazing filler alloys (as well as solders), whether metallic or ceramic. The diagram shows the phase or phases that exist under equilibrium conditions as a function of alloy composition and temperature; it is, in that sense, a ''phase map.'' This type of constitutional diagram is called a ''simple eutectic system with partial solid solubility in the terminal phases.'' It is ''simple'' in that only one phase reaction (i.e., a eutectic reaction) occurs between pure Cu and pure Ag. (In more complex systems, there are intermediate phases and various reactions between the terminal phases and/or pure materials.) The other major type of constitutional diagram appropriate to brazing filler alloys is the eutectic system with no solid solubility of one or the other elemental component (or both) in each other. The only difference is that instead of having terminal phases that are solid solutions, this latter type of system has terminal phases that are pure materials.

The highest temperature at which a crystalline metal or ceramic or alloy is completely solid is called the ''solidus temperature'' (or ''solidus''), while the lowest temperature at which a crystalline metal or ceramic alloy is completely liquid is called the ''liquidus temperature'' (or ''liquidus''). Between the solidus and liquidus, an alloy consists of both a liquid and a solid phase in equilibrium. In the process of brazing (and also the process of soldering), the solidus is considered the melting point of the brazing filler material and the liquidus is considered its flow point.

In Figure 7.9, the solidus temperatures of all alloy compositions from pure silver to pure copper, with all compositions in between, are given by the solidus line ADCEB. This line represents the start of melting when any alloy in the system is heated. The liquidus temperatures of all alloy compositions are given by the liquidus line ACB. This line represents the temperatures at which all alloy compositions become completely liquid upon heating or just begin to form solid upon cooling (i.e., just begin to solidify upon cooling).

At point A, pure Ag melts at a single temperature (i.e., 961°C (1,762°F)), while at point B pure Cu also melts at a single temperature (i.e., 1,083°C (1,981°F)). At point C, the two lines representing the liquidus and the solidus temperatures meet, indicating that a particular alloy (i.e., 72 wt.% Ag/28 wt.% Cu) melts at a discrete temperature and at the lowest temperature of any composition for the simple system. This point is called the ''eutectic point,'' and the alloy is called the ''eutectic alloy.''

The alloy of eutectic composition is as fluid as the pure components that comprise it, since there is no solid present, ever. At all other compositions, melting occurs over a range of temperatures between the liquidus and the solidus, and the alloy is made up of a

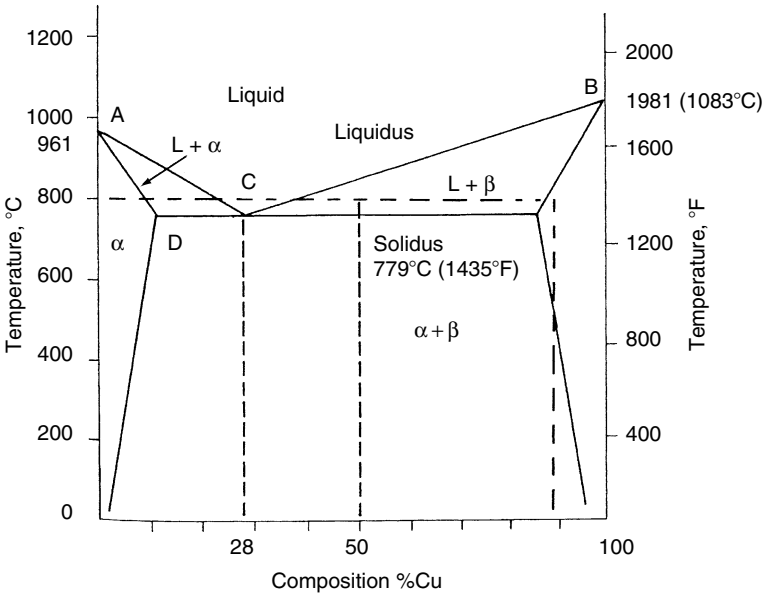

Figure 7.9 Constitutional diagram for the Cu–Ag binary system of alloys, many of which are used as braze fillers. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 8.4, page 295, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

liquid and a solid phase and is mushy, like slushy snow that consists of solid ice crystals and water. How fluid this mixture is depends on the relative proportions of liquid and solid present. The greater the proportion of solid, the less fluid the mixture; virtually all fluidity disappears at the point at which the proportion of solid allows all of the solid to touch and thereby create a somewhat rigid network or "skeleton."

The Ag-rich end of the diagram is terminated with a substitutional solid solution of Cu in Ag called α. The Cu-rich end of the diagram is terminated with a substitutional solid solution of Ag in Cu called β. The central compositions consist of an intimate mixture of α and β solid solutions, actually: α plus α−β containing eutectic below 72 wt.% Ag/28 wt.% Cu; β plus α−β containing eutectic above 72 wt.% Ag/28 wt.% Cu; and just α−β containing eutectic at 72 wt.% Ag/28 wt.% Cu. At any particular composition and temperature, the proportions of liquid and solid phase making up the mixture (and creating a mushy state) can be calculated from the "lever rule" (see any basic textbook on materials science). For example, a 50 wt.% Ag/50 wt.% Cu alloy at 800°C (1,472°F) contains the following proportions of liquid and solid β:

$$\%\,\text{liquid L} = (88 - 50)/(88 - 37) \times 100\% = 74.5\%$$

and

$$\%\,\text{solid } \beta = (50 - 37)/(88 - 37) \times 100\% = 25.5\%$$

Above the liquidus, the Cu and Ag atoms are thoroughly interspersed as a liquid solution.

Solidification in the off-eutectic regions occurs as described in Chapter 9, Subsection 9.3.4. However, solidification by the eutectic reaction is more complex in its details. An excellent description of the details is given in Messler (1999).

7.5.4 Braze Filler Alloy Types

The American Welding Society (AWS), in its "Specification for Brazing Filler Metal," AWS A5.8, lists eight categories of brazing filler metal types. These are presented in Table 7.3 and include the following categories:

Aluminum–Silicon Alloys (designated BAlSi). Al–Si alloys are used primarily for brazing Al and its alloys to themselves, to one another, or to various other metals and alloys. Because of the presence of tenacious oxide on Al and its alloys, these fillers require an aggressive flux.

Magnesium Alloys (designated BMg). Mg alloys are used for brazing Mg and its alloys to themselves, and, because of the presence of a tenacious oxide, always requires an aggressive flux.

Copper and Copper–Zinc Alloys (designated BCu or RBCuZn). Cu and Cu–Zn alloys are widely used with both ferrous and non-ferrous metals and alloys. They are, without question, the "workhorse" braze alloys. As a group, they have limited corrosion resistance, but are highly fluid. They may or may not require fluxes, depending on the base material being brazed.

Copper–Phosphorus Alloys (designated BCuP). Cu–P alloys are good for brazing Cu and Cu alloys to themselves or to one another; however, they tend to suffer from liquation.

Silver Alloys (designated BAg). Expensive but popular, Ag alloys are used for brazing most ferrous and non-ferrous metals and alloys, except Al and Mg. They offer excellent flow.

Gold Alloys (designated BAu). Very expensive, Au alloys are used for brazing parts in electronic assemblies and vacuum tubes, where volatile components are undesirable and where electrical conductivity must be high. They offer excellent corrosion resistance with Fe, Ni, and Co alloys.

Nickel Alloys (designated BNi). Ni alloys are used for corrosion and heat resistance (up to 980°C (1,800°F) continuous, or 1,200°C (2,200°F) short-term). They are excellent in vacuum systems and they are the choice for use with Ni-base alloys.

Table 7.3 AWS Classification of Braze Filler Alloys

	Brazing Temperature Range		
AWS Classification	*°F*	*°C*	*Nominal Composition (%)*
Aluminum–silicon alloys			
BAlSi-2	1110–1150	599–621	92.5 Al, 7.5 Si
BAlSi-3	1060–1120	571–601	86 Al, 10 Si, 4 Cu
BAlSi-4	1080–1120	582–604	88 Al, 12 Si
BAlSi-5	1090–1120	588–604	90 Al, 10 Si
Magnesium alloys			
BMg-1	1120–1160	604–627	89 Mg, 2 Zn, 9 Al
BMg-2a	1080–1130	582–610	83 Mg, 5 Zn, 12 Al
Copper–phosphorus alloys			
BCuP-1	1450–1700	788–927	95 Cu, 5P
BCuP-2	1350–1550	732–843	93 Cu, 7 P
BCuP-3	1300–1500	704–816	89 Cu, 5 Ag, 6 P
BCuP-4	1300–1450	704–788	87 Cu, 6 Ag, 7 P
BCuP-5	1300–1500	704–816	80 Cu, 15 Ag, 5 P
Copper–copper zinc alloys			
BCu-1	2000–2100	1093–1149	99.9 Cu (min)
BCu-1a	2000–2100	1093–1149	99.0 Cu (min)
BCu-2	2000–2100	1093–1149	86.5 Cu (min)
RBCuZn-A	1670–1750	910–954	57 Cu, 42 Zn, 1 Sn
RBCuZn-D	1720–1800	938–982	47 Cu, 11 Ni, 42 Zn
Silver alloys			
BAg-1	1145–1400	618–760	45 Ag, 15 Cu, 16 Zn, 24 Cd
BAg-1a	1175–1400	635–760	45 Ag, 15 Cu, 16 Zn 24 Cd
BAg-2	1295–1550	700–843	45 Ag, 26 Cu, 21 Zn, 18 Cd
BAg-2a	1310–1550	710–843	30 Ag, 27 Cu, 23 Zn, 20 Cd
BAg-3	1270–1500	688–816	52 Ag, 15 Cu, 15 Zn, 15 Cd, 3 Ni
BAg-4	1435–1650	780–899	40 Ag, 30 Cu, 23 Zn, 2 Ni
BAg-5	1370–1550	743–843	45 Ag, 30 Cu, 25 Zn
BAg-6	1425–1600	774–871	53 Ag, 31 Cu, 16 Zn
BAg-7	1205–1400	651–760	56 Ag, 22 Cu, 17 Zn, 5 Sn
BAg-8	1435–1650	780–899	77 Ag, 23 Cu
BAg-8a	1410–1600	766–871	77 Ag, 23 Cu
BAg-13	1575–1775	857–635	54 Ag, 40 Cu, 5 Zn, 1 Ni
BAg-13a	1600–1800	871–982	56 Ag, 42 Cu, 2 Ni
BAg-18	1325–1550	718–843	60 Ag, 40 Cu
BAg-19	1610–1800	877–982	92 Ag, 8 Cu
Precious metals			
BAu-1	1860–2000	1016–1093	37 Au, 63 Cu
BAu-2	1635–1850	890–1010	79.5 Au, 20.5 Cu
BAu-3	1885–1995	1030–1090	34 Au, 62 Cu, 4 Ni
BAu-4	1740–1840	949–1004	82 Au, 18 Ni
Nickel alloys			
BNi-1	1950–2200	1066–1204	14 Cr, 3 Br, 4 Si, 4 Fe, 75 Ni
BNi-2	1850–2150	1010–1177	7 Cr, 3 Br, 4 Si, 3 Fe, 83 Ni
BNi-3	1850–2150	1010–1177	3 Br, 4 Si, 2 Fe, 91 Ni
BNi-4	1850–2150	1010–1177	1 Br, 3 Si, 2 Fe, 94 Ni
BNi-5	2100–2200	1149–1204	19 Cr, 10 Si, 71 Ni
BNi-6	1700–1875	927–1025	11 Br, 89 Ni
BNi-7	1700–1900	927–1038	13 Cr, 10 Br, 77 Ni

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Cobalt Alloys (designated BCo). Co alloys are used for service at high temperatures and for compatibility with Co alloys.

Table 7.4 Brazing Fillers for Use with Refractory Metals and Alloys

Brazing Filler Metal	*Liquidus Temperature*		*Brazing Filler Metal*	*Liquidus Temperature*	
	°C	*°F*		*°C*	*°F*
Cb	2416	4380	Mn–Ni–Co	1021	1870
Ta	2997	5425			
Ag	960	1760	Co–Cr–Si–Ni	1899	3450
Cu	1082	1980	Co–Cr–W–Ni	1427	2600
Ni	1454	2650	Mo–Ru	1899	3450
Ti	1816	3300	Mo–B	1899	3450
Pd–Mo	1571	2860	Cu–Mn	871	1600
Pt–Mo	1774	3225	Cb–Ni	1190	2175
Pt–30W	2299	4170			
Pt–50Rh	2049	3720	Pd–Ag–Mo	1306	2400
			Pd–Al	1177	2150
Ag–Cu–Zn–Cd–Mo	619–701	1145–1295	Pd–Ni	1205	2200
Ag–Cu–Zn–Mo	718–788	1325–1450	Pd–Cu	1205	2200
Ag–Cu–Mo	780	1435	Pd–Ag	1306	2400
Ag–Mn	971	1780	Pd–Fe	1306	2400
			Au–Cu	885	1625
Ni–Cr–B	1066	1950	Au–Ni	949	1740
Ni–Cr–Fe–Si–C	1066	1950	Au–Ni–Cr	1038	1900
Ni–Cr–Mo–Mn–Si	1149	2100	Ta–Ti–Zr	2094	3800
Ni–Ti	1288	2350			
Ni–Cr–Mo–Fe-W	1305	2380	Ti–V–Cr–Al	1649	3000
Ni–Cu	1349	2460	Ti–Cr	1481	2700
Ni–Cr–Fe	1427	2600	Ti–Si	1427	2600
Ni–Cr–Si	1121	2050	Ti–Zr– Be[b]	999	1830
			Zr–Cb–Be[b]	1049	1920
			Ti–V–Be[b]	1249	2280
			Ta–V–Cb[b]	1816–1927	3300–3500
			Ta–V–Ti[b]	1760–1843	3200–3350

[a]Not all the filler metals listed are commercially available.
[b]Depends on the specific composition.
Reprinted with permission from *Welding Handbook*, Vol. 2, 8th Ed., American Welding Society, 1991, page 395.
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In addition to these major categories, there are specialty braze fillers. One example is fillers for brazing refractory metals and alloys, some examples of which are listed in Table 7.4. Table 7.5 lists various base metal–filler metal combinations.

Metal braze alloy fillers can be used for brazing metals to metals, metals to ceramics, or ceramics to ceramics, including graphite and other carbonaceous materials to themselves and to metals. Braze filler alloys are commonly listed under the base metals or ceramics for which they are most suited. Just to show the diversity of alloys available within the AWS categories, Table 7.6 lists BAg filler alloys suitable for brazing

Table 7.5 Base Metal–Braze Filler Metal Combinations

	Al & Al Alloys	*Mg & Mg Alloys*	*Cu & Cu Alloys*	*Carbon & Low Alloy Steels*	*Cast Iron*	*Stainless Steel*	*Ni & Ni Alloys*	*Ti & Ti Alloys*	*Be, Zr, & Alloys (Reactive Metals)*	*W, Mo, Ta, Cb, & Alloys (Refractory Metals)*	*Tool Steels*
Al & Al alloys	BAlSi										
Mg & Mg alloys	X	BMg									
Cu & Cu alloys	X	X	BAg, BAu, BCuP, RBCuZn	BNi							
Carbon & low alloy steels	BAlSi	X	BAg, BAu, RBCuZN, BNi	BAg, BAu, BCu, RBCuZn, BNi							
Cast iron	X	X	BAg, BAu, RBCuZN, BNi	BAg, RBCuZn, BNi	BAg, RBCuZn, BNi						
Stainless steel	BAlSi	X	BAg, BAu	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi					
Ni & Ni alloys	X	X	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, RBCuZn, BNi	BAg, BCu, RBCuZn	BAg, BAu, BCu, BNi	BAg, BAu, BCu, BNi				
Ti & Ti alloys	BAlSi	X	BAg	BAg	BAg	BAg	BAg	Y			
Be, Zi, & alloys (reactive metals)	X BAlSi(Be)	X	BAg	BAg, BNi[a]	BAg, BNi[a]	BAg, BNi[a]	BAg, BNi[a]	Y	Y		
W, Mo, Ta, Cb, & alloys (refractory metals)	X	X	BAg, BNi	BAg, BCu, BNi[a]	BAg, BCu, BNi[a]	BAg, BCu, BNi[a]	BAg, BCu, BNi[a]	Y	Y	Y	
Tool steels	X	X	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, RBCuZn, BNi	BAg, BAu, RBCuZn, BNi	BAg, BAu, BCu, BNi	BAg, BAu, BCu, RBCuZn, BNi	X	X	X	BAg, BAu, BCu, RBCuZn, BNi

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Note: Refer to AWS Specification A5.8 for information on the specific compositions within each classification.
X—Not recommended; however, special techniques may be practicable for certain dissimilar metal combinations.
Y—Generalizations on these combinations cannot be made. Refer to the Brazing Handbook for usable filler metals.
[a]—Special brazing filler metals are available and are used successfully for specific metal combinations.

Filler Metals:

BAlsi—Aluminum	BCuP—Copper phosphorus	BAg—Silver base	RBCuZn—Copper zinc
BAu—Gold base	BMg—Magnesium base	BCu—Copper	BNi—Nickel base

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Table 7.6 Silver-Based Braze Filler Alloys for Use with Stainless Steels

Filler Metal	Composition, %								Other Elements (total)	Solidus Temperature		Liquidus Temperature		Brazing Temperature Range	
	Ag	Cu	Zn	Cd	Ni	Sn	Li	Mn		°C	°F	°C	°F	°C	°F
BAg-1	44.0–46.0	14.0–16.0	14.0–18.0	23.0–25.0	...	...	...	...	0.15	607	1125	618	1145	618–760	1145–1400
BAg-1a	49.0–51.0	14.5–16.5	14.5–18.5	17.0–19.0	...	...	...	...	0.15	627	1160	635	1175	635–760	1175–1400
BAg-2	34.0–36.0	25.0–27.0	19.0–23.0	17.0–19.0	...	...	...	...	0.15	607	1125	701	1295	701–843	1295–1550
BAg-2a	29.0–31.0	26.0–28.0	21.0–25.0	19.0–21.0	...	...	...	...	0.15	607	1125	710	1310	710–843	1310–1550
BAg-3	49.0–51.0	14.5–16.5	13.5–17.5	15.0–17.0	2.5–3.5	...	...	...	0.15	632	1170	688	1270	688–816	1270–1500
BAg-4	39.0–41.0	29.0–31.0	26.0–30.0	...	1.5–2.5	...	...	...	0.15	671	1240	779	1435	779–899	1435–1650
BAg-5	44.0–46.0	29.0–31.0	23.0–27.0	...	...	...	...	...	0.15	677	1250	743	1370	743–843	1370–1550
BAg-6	49.0–51.0	33.0–35.0	14.0–18.0	...	...	...	...	...	0.15	688	1270	774	1425	774–871	1425–1600
BAg-7	55.0–57.0	21.0–23.0	15.0–19.0	...	...	4.5–5.5	...	...	0.15	618	1145	651	1205	651–760	1205–1400
BAg-8	71.0–73.0	Rem	...	...	...	...	...	...	0.15	779	1435	779	1435	779–899	1435–1650
BAg-8a	71.0–73.0	Rem	...	...	...	...	0.25–0.50	...	0.15	766	1410	766	1410	766–871	1410–1600
BAg-9	64.0–66.0	19.0–21.0	13.0–17.0	...	...	...	...	...	0.15	671	1240	713	1325	713–843	1325–1550
BAg-10	69.0–71.0	19.0–21.0	8.0–12.0	...	...	...	...	...	0.15	690	1275	738	1360	738–843	1360–1550
BAg-13	53.0–55.0	Rem	4.0–6.0	...	0.5–1.5	...	...	...	0.15	713	1325	857	1575	857–969	1575–1775
BAg-13a	55.0–57.0	Rem	...	...	1.5–2.5	...	...	...	0.15	771	1420	893	1640	871–982	1600–1800
BAg-18	59.0–61.0	Rem	...	...	...	9.5–10.5	...	...	0.15	601	1115	713	1325	713–843	1325–1550
BAg-19	92.0–93.0	Rem	...	...	...	...	0.15–0.30	...	0.15	760	1400	885	1635	877–982	1610–1800
BAg-20	29.0–31.0	37.0–39.0	30.0–34.0	...	...	...	...	...	0.15	677	1250	766	1410	766–871	1410–1600
BAg-21	62.0–64.0	27.5–29.5	...	...	2.0–3.0	5.0–7.0	...	...	0.15	690	1275	801	1475	801–899	1475–1650
BAg-22	48.0–50.0	15.0–17.0	21.0–25.0	...	4.0–5.0	...	...	7.0–8.0	0.15	682	1260	699	1290	699–830	1290–1525
BAg-23	84.0–86.0	...	...	...	...	...	...	Rem	0.15	960	1760	971	1780	971–1038	1780–1900
BAg-24	49.0–51.0	19.0–21.0	26.0–30.0	...	1.5–2.5	...	...	...	0.15	660	1220	707	1305	707–843	1305–1550
BAg-25	19.0–21.0	39.0–41.0	33.0–37.0	...	...	...	...	4.5–5.5	0.15	738	1360	790	1455	790–846	1455–1555
BAg-26	24.0–26.0	37.0–39.0	31.0–35.0	...	1.5–2.5	...	...	1.5–2.5	0.15	707	1305	801	1475	801–871	1475–1600
BAg-27	24.0–26.0	34.0–36.0	24.5–28.5	12.5–14.5	...	...	...	...	0.15	607	1125	746	1375	746–857	1375–1575
BAg-28	39.0–41.0	29.0–31.0	26.0–30.0	...	...	1.5–2.5	...	...	0.15	649	1200	710	1310	710–843	1310–1550

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stainless steels. There are literally thousands of commercially available brazing filler alloys and probably an equal or larger number of proprietary or specialty fillers.

7.5.5 Ceramic Braze Fillers

Ceramics can be joined to themselves or to metals by brazing with braze fillers that are themselves ceramics. Glasses are a common ceramic braze or "solder"[10] material, since glasses soften and flow well at elevated temperatures, albeit not well enough to operate entirely using capillary action. However, mixtures of glasses and crystalline ceramics, or even all crystalline ceramics, often as eutectics, can be used as braze filler materials.

The same criteria apply for selecting *ceramic braze fillers* as for selecting metal braze fillers (i.e., they must have low melting temperatures relative to the substrates for selecting which they are intended, they must wet the substrate(s), they must be fluid, they should not phase-separate or "liquate," and they should have appropriate mechanical, chemical, and physical properties for the intended application). Chapter 12 discusses ceramic braze fillers in more detail, when the joining of ceramics and glasses is addressed specifically, but Table 7.7 lists some important ceramic braze fillers.

7.5.6 Brazeability and its Assessment

The base material has a prime effect on the strength and durability of a brazed joint. Obvious factors include the strength of the base material, the strengthening mechanism(s) operating in the base material (especially mechanisms dependent on heat treatments), the coefficient of thermal expansion of the base material compared to the filler, and the reactivity of the base material. High-strength base materials, especially high strength metals, tend to produce higher strength braze joints. Most important of all, however, is the receptivity of the base material to brazing in the first place, and this depends on the ease or difficulty of wetting the base material. Table 7.8 lists the relative ease of brazing various base materials (i.e., their *brazeability*).

7.6 BRAZING FLUXES AND ATMOSPHERES

7.6.1 The Need for Fluxes or Atmospheres in Brazing

Metals and alloys tend to react with various constituents of the atmosphere to which they are exposed. This tendency increases as the temperature is raised and is especially strong once melting occurs. The most common reaction is oxidation, but nitrides (in nitrification), carbides (in carburization, as well as in decarburization), and hydrides are sometimes formed. Any of these reaction products hinders the production of consistently sound braze joints. Fluxes, gas atmospheres, and vacuum are used to exclude reactants and thus prevent undesirable reactions during brazing. Under some

[10] See the discussion of "solder glasses" in Subsection 12.8.4 of Chapter 12.

Table 7.7 Important Metallic and Ceramic Braze Fillers for Joining Ceramics to Other Ceramics or to Metals

Active Metal Braze Fillers for Ceramics			
Alloy System	*Composition (wt.%)*	*Liquidus (°C/°F)*	*Solidus (°C/°F)*
AgTi	96Ag–4Ti	970/1778	970/1778
AgCuTi	91Ag–6Cu–3Ti	917/1683	875/1607
AgCuTi	70.5Ag–27.5Cu–2Ti	795/1463	780/1436
AgCuTi	70.5Ag–26.5Cu–3Ti	857/1575	803/1477
AgCuTi	64Ag–34.5Cu–1.5Ti	810/1490	770/1418
AgCuTi	63Ag–35.25Cu–1.75Ti	815/1499	780/1436
AgCuAlTi	92.75Ag–5Cu–1Al–1.25Ti	912/1674	860/1580
AgCuInTi	72.5Ag–19.5Cu–5In–3Ti	760/1400	730/1346
AgCuInTi	61.5Ag–24Cu–14.5In–(Ti)	710/1310	620/1148
AgCuInTi	59Ag–27.25Cu–12.5In–1.25Ti	715/1320	605/1121
AgCuNiTi	71.5Ag–28Cu–0.5Ni–(Ti)	795/1463	780/1436
AgCuNiTi	56Ag–42Cu–2Ni–(Ti)	895/1643	770/1418
AgCuSnTi	63Ag–34.25Cu–1Sn–1.75Ti	806/1483	775/1427
AuNiTi	96.4Au–3Ni–0.6Ti	1,030/1886	1,003/1837
CuAlSiTi	92.75Cu–2Al–3Si–2.25Ti	1024/1875	958/1756
PbInTi*	92Pb–4In–4Ti	325/617	320/606
SnAgTi*	86Sn–10Ag–4Ti	300/572	221/430
TiCuAg	68.8Ti–26.7Cu–4.5Ag	850/1560	830/1526
TiCuNi	70Ti–19Cu–11Ni	960/1760	910/1670

Ceramic-Based Braze Fillers for Ceramics			
Alloy System	*Composition*	*Liquidus (°C/°F)*	*Solidus (°C/°F)*
Oxynitride glasses	$[Si, Al]_3[O, N]_4$ SiAlON		up to 1,250/2,282
Oxide mixtures	Al_2O_3, MnO, SiO_2		up to 750/1,382
Oxide mixtures	Al_2O_3, CaO, MgO, SiO_2		up to 1,700/3,072
Yttria–Alumina	Y_2O_3–Al_2O_3 eutectic		1,760/3,200
Glass–ceramics	SiO_2, Al_2O_3, P_2O_5, boric oxide alkali metal oxides		N/A
Non-metallic glasses	$35CaO-25TiO_2-40SiO_2$ (CTS glass)		N/A

*Actually, these are solders, not braze fillers, as the solidus is lower than 425°C (840°F)

conditions, fluxes and atmospheres may also actually reduce oxides or other tarnish layers that are present, clean the metal surface, and refine the bulk melt of the filler.

7.6.2 Fluxes for Brazing

A *flux* is a non-metallic chemical compound that will react with metal oxides or other tarnish layers (such as sulfides) that are the result of chemical oxidation reactions, and clean the metal. Typically, fluxes contain chlorides, fluorides, fluoroborates, borax, or

Table 7.8 Relative Ease of Brazing Various Base Materials

Degree of Difficulty	*Materials*
Easy	• Cu, Ni, Co, and their alloys • Steels • Precious Metals
Fair	• Al, W, Mo, Ta, and alloys with more than 5% of metals that form refractory oxides • Cast iron • WC
Difficult	• Ti, Zr, Be, and their alloys • Ceramics • Graphite • Glass
Impossible	• None

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borates of active metals (such as Na, K, Ca, or Ba), boric acid, wetting agents, and water. To effectively protect the surface of metals that are to be brazed, a flux must completely cover and protect those surfaces until the brazing temperature is reached. The flux must then remain chemically active and react throughout the brazing cycle. Fluxes become active and effective in their molten state. The viscosity and surface tension of the flux and the interfacial (surface) energy between the flux and the substrate are important since the molten filler metal must be able to displace the molten flux from the joint at the brazing temperature.

There is no single flux that is best for all brazing applications. Rather, fluxes must be matched to the application by considering the base metal and the particular brazing process. Brazing fluxes are classified by the AWS into six groups by base metal and are recommended for use in rather specific temperature ranges. Table 7.9 lists these classes and use temperatures. Within a particular AWS type, there are several criteria for selecting a specific flux for maximum effectiveness (1) for dip brazing, water (including water of hydration) must be avoided in fluxes (as this would lead to explosive release of steam); (2) for resistance brazing, the flux must be electrically conductive (usually wet and dilute); (3) the ease of removal of flux residue should be considered (as leaving residue on a part can lead to subsequent localized corrosive attack); and (4) the corrosive action of the flux to the filler and substrate should be minimal to do the job.

Fluxes are available in a variety of physical forms, including dry powders, pastes (containing water or other solvents and/or wetting agents), and liquids. The form selected depends on the individual work requirements, the specific brazing process, and the particular brazing procedure.

Flux residue and excess flux must always be thoroughly removed from the finished brazement as soon as possible after brazing has been completed; otherwise

Table 7.9 List of Fluxes for Brazing Various Base Materials

AWS Brazing Flux Type No.	*Base Metals Being Brazed*	*Recommended Filler Metals*	*Recommended Useful Temp. Range* °F	°C	*Major Flux Ingredients*	*Forms Available*
1	All brazeable aluminum alloys	BAlSi	700–1190	371–643	Chlorides Fluorides	Powder
2	All brazeable magnesium alloys	BMg	900–1200	482–649	Chlorides Fluorides	Powder
3A	Copper and copper-base alloys (except those with aluminum) iron-base alloys; cast iron; carbon and alloy steel; nickel and nickel-base alloys; stainless steels; precious metals	BCuP BAg	1050–1600	566–871	Boric acid Borates Fluorides Fluoroborates Wetting agents	Powder Paste Liquid
3B	Copper and copper-base alloys (except those with aluminum); iron-base alloys; cast iron; carbon and alloy steel; nickel and nickel-base alloys; stainless steel; precious metals	BCu BCuP BAg BAu RBCu Zn BNi	1350–2100	732–1149	Boric acid Borates Fluorides Fluoroborates Wetting agents	Powder Paste Liquid
4	Aluminum bronze, aluminum brass- and iron- or nickel-base alloys containing minor amounts of Al and/or Ti	BAg (all) BCuP (copper-base alloys only)	1050–1600	566–871	Chlorides Fluorides Borates Wetting agent	Powder Paste
5	Same as 3A and 3B above	Same as 3B excluding BAg through 7)	1400–2200	760–1204	Borax Boric acid Borates Wetting agent	Powder Paste Liquid

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corrosion can occur. Methods for removing flux and flux residues include washing in hot water, taking advantage of thermal shock by quenching to break up brittle oxides or other non-metallics, and often using agitation or scrubbing. Chemical cleaners (e.g., solvents, acids, or alkalis) can be used, as can some mechanical aids (e.g., ultrasonics, shot or grit blasting). Many of the cleaning procedures are similar to those used for proper preparation of adherends for adhesive bonding (see Chapter 4, Subsection 4.5.2).

7.6.3 Controlled Atmospheres for Brazing

Controlled atmospheres or a vacuum can be employed to prevent the formation of oxides during brazing and, in many instances, to remove light oxide or other tarnish layers to promote wetting and flow of molten braze filler. Techniques include (1) the use of gaseous atmospheres alone; (2) the use of gaseous atmospheres together with fluxes; (3) the use of high vacuums; and (4) combinations of vacuum and gaseous atmospheres.

Gaseous atmospheres include pure forms and mixtures of CO_2, CO, H_2, inert gases (such as Ar), N_2, and CH_4. Of these, CO and H_2 are reducing, while the others are simply inert or relatively inert. Table 7.10 lists the AWS categories of atmospheres for brazing. It should be noted that controlling the moisture content of the atmosphere (i.e., the "dew point") is extremely important to avoid oxidation by water vapor. Recommended maximum dew points are also given in Table 7.10.

7.7 BRAZE JOINT DESIGN

From a mechanical standpoint, the design of a brazement is no different than the design of any other part or assembly. Static loading, dynamic loading, stress concentrations, and environmental factors must all be considered. In addition, some important factors specific to brazements include (1) the composition of the base materials and the filler; (2) the type and design of the joint; and (3) the service requirements, including mechanical performance, electrical or thermal conductivity, pressure tightness (or hermeticity), corrosion resistance, and service temperature. In general, the strength of the filler metal in a brazed joint is lower than the strength of the base materials. The specific joint strength will vary according to the joint clearance (i.e., initial gap), degree of filler–substrate interaction (as this leads to the formation of a weak boundary layer), and presence of defects in the joint.

Basically, two types of joints are used in brazing designs, the lap joint and the butt joint. A variant of the butt joint that forces loading more toward shear is called the "scarf joint," and should be familiar from adhesive bonding (Chapter 4, Subsection 4.6.3). These joint types are shown in Figure 7.10. In lap joints, overlap of at least three times the thickness of the thinnest joint element will usually yield the maximum joint efficiency. Scarf joints are attractive because they increase the joint area without increasing the thickness of the joint members. Figure 7.11 illustrates some lap and butt joint designs for various static and dynamic loading situations.

Table 7.10 Atmospheres for Brazing (Using the AWS Classification Scheme)

AWS brazing atmosphere type number	*Source*	*Maximum dew point of incoming gas*	*Approximate composition, %*				*Application*		*marks*
			H_2	N_2	CO	CO_2	*Filler metals*[e]	*Base metals*	
1	Combusted fuel gas (low hydrogen)	Room temp.	5–1	87	5–1	11–12	BAg,[a] BCuP, RBCuZn[a]	Copper, brass[a]	
2	Combusted fuel gas (decarburizing)	Room temp.	14–15	70–71	9–10	5–6	BCu, BAg[a], RBCuZn[a], BCuP	Copper[b], brass[a], low carbon steel, nickel, monel, medium carbon steel[c]	Decarburizes
3	Combusted fuel gas, dried	−40°C(−40°F)	15–16	73–75	10–11		Same as 2	Same as 2 plus medium and high carbon steels, monel, nickel alloys	
4	Combusted fuel gas, dried (carburizing)	−40°C(−40°F)	38–40	41–45	17–19		Same as 2	Same as 2 plus medium and high carbon steels	Carburizes
5	Dissociated ammonia	−54°C(−65°F)	75	25			BAg[a], BCuP, RBCuZn[a], BCu, BNi	Same as for 1, 2, 3, 4, plus alloys containing chromium[d]	
6	Cylinder hydrogen	Room temp.	97–100				Same as 2	Same as 2	Decarburizes
7	Deoxygenated and dried hydrogen	−59°C(−75°F)	100				Same as 5	Same as 5 plus cobalt, chromium, tungsten alloys, and carbides[d]	
8	Heated volatile materials	Inorganic vapors (i.e., zinc, cadmium, lithium, volatile fluorides)					BAg	Brasses	Special purpose. May be used in conjunction with 1 through 7 to avoid use of flux
9	Purified inert gas	Inert gas (e.g., helium, argon, etc.)					Same as 5	Same as 5 plus titanium, zirconium, hafnium	Special purpose. Parts must be *very* clean and atmosphere must be pure

(*Continues*)

Table 7.10 (*Continued*)

AWS brazing atmosphere type number	*Source*	*Maximum dew point of incoming gas*	*Approximate composition, %*				*Application*		*Remarks*
			H_2	N_2	CO	CO_2	*Filler metals*[e]	*Base metals*	
10	Vacuum	Vacuum above 2 Torr[f]					BCuP, BAg	Cu	
10A	Vacuum	0.5 to 2 Torr					BCu, BAg	Low carbon steel, Cu	
10B	Vacuum	0.001 to 0.5 Torr					BCu, BAg	Carbon and low alloy steels, Cu	
10C	Vacuum	1×10^{-3} Torr and lower					BNi, BAu, BAlSi, Ti alloys	Heat- and corrosion-resisting steels, Al, Ti, Zr, refractory metals	

Note: AWS Types 6, 7, and 9 include reduced pressures down to 2 Torr.
[a] Flux is required in addition to atmosphere when alloys containing volatile components are used.
[b] Copper should be fully deoxidized or oxygen free.
[c] Heating time should be kept to a minimum to avoid objectionable decarburization.
[d] Flux must be used in addition if appreciable quantities of aluminum, titanium, silicon, or beryllium are present.
[e] See Table 8.2 for explanation of filler metals.
[f] 1 Torr = 133 Pa.
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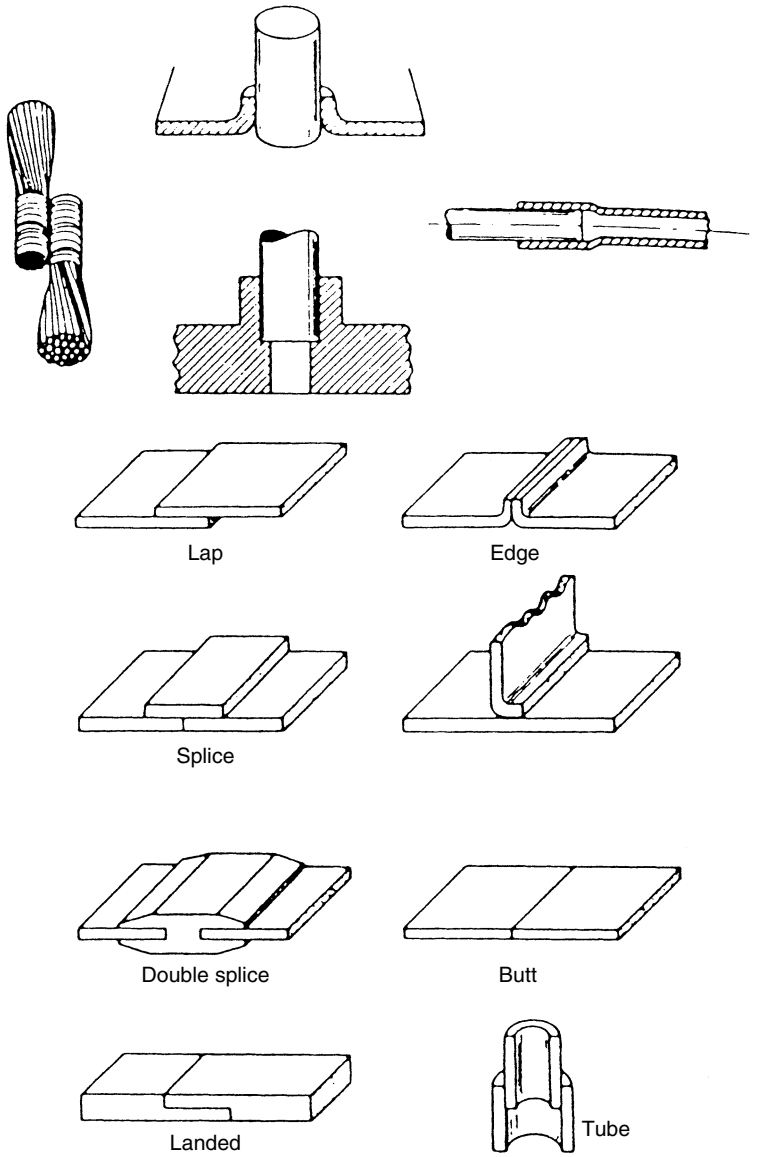

Figure 7.10 Schematic illustration of some common arrangements of parts in a braze assembly. (Reprinted from *Modern Welding Technology*, 5th edition, Howard B. Cary, Fig. 7.21, page 221, Prentice Hall, Upper Saddle River, NJ, 2002, with permission of Pearson Education, Inc., Upper Saddle River, NJ.)

Joint clearance, or "gap," is a key parameter in the design and production of brazed joints (as they are for adhesive-bonded and soldered joints), for several reasons. First, the clearance in a joint is important purely from the standpoint of the effect of

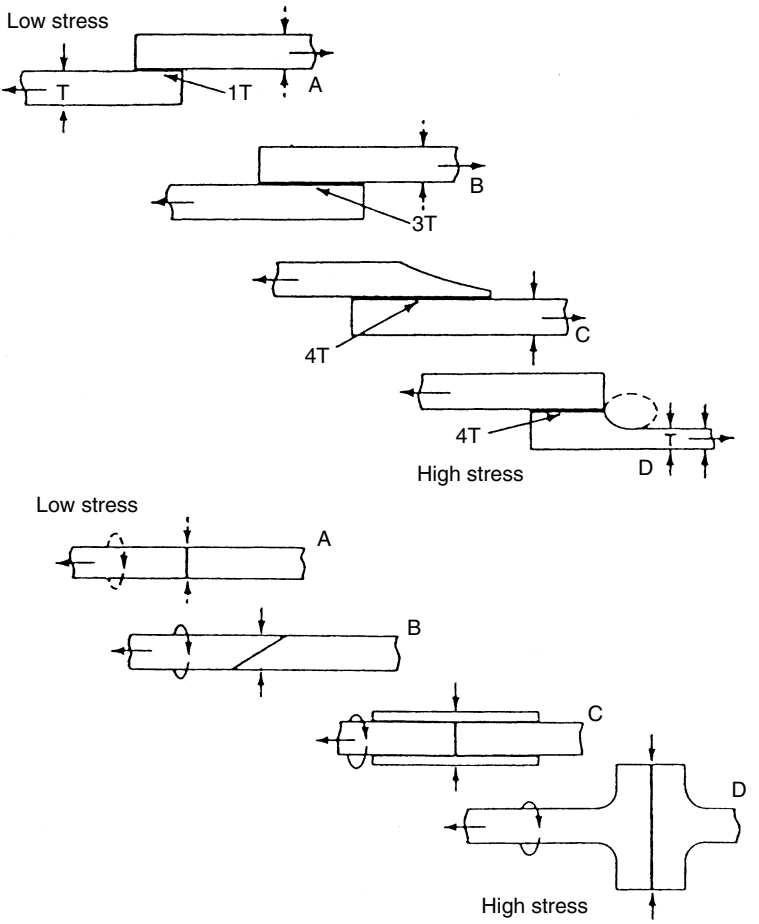

Figure 7.11 Schematic illustration of some of the typical joint designs used in brazing. (Reprinted from *Welding Handbook*, 8th ed., Vol. 2, *Welding Processes*, Fig. 12, page 407, American Welding Society, Miami, FL, 1991, with permission of the American Welding Society, Miami, FL.)

mechanical restraint. The plastic flow of the braze filler is restrained by the higher strength base material only if the filler does not get too thick. On the other hand, for purposes of strain accommodation, the braze filler layer cannot be too thin either. Second, joint clearance must be sufficient to prevent the entrapment of slag formed from fluxes or gas released by volatiles or absorbed from atmospheres and trapped in the form of voids. Third, the relationship between joint clearance and capillary force controls proper flow and distribution of the filler. Fourth, for diffusion brazing, clearance controls the amount of filler metal that must be diffused away. Table 7.11 gives the recommended joint clearances for brazing with various filler classes.

Finally, it is vitally important that the braze filler completely fills the joint and that defects are avoided during brazing. Defects to be avoided include voids

Table 7.11 Recommended Joint Clearances for Brazing

Filler Metal AWS Classification	*Joint Clearance*		*Brazing Conditions*
	Inches	*Millimeters*	
BA1Si group	0.002–0.008	0.051–0.203	For length of lap less than $\frac{1}{4}$ in. (6.4 mm)
	0.008–0.010	0.203–0.254	For length of lap greater than $\frac{1}{4}$ in. (6.4 mm)
BCuP group	0.001–0.005	0.025–0.127	No flux or mineral brazing fluxes
BAg group	0.002–0.005	0.051–0.127	Mineral brazing fluxes
	0.000–0.002	0.000–0.051	Gas atmosphere brazing fluxes
BAu group	0.002–0.005	0.051–0.127	Mineral brazing fluxes
	0.000–0.002	0.000–0.051	Gas atmosphere brazing fluxes
BCu group	0.000–0.002	0.000–0.051	Gas atmosphere brazing fluxes
BCuZn group	0.002–0.005	0.051–0.127	Mineral brazing fluxes
BMg	0.004–0.010	0.102–0.254	Mineral brazing fluxes
BNi group	0.002–0.005	0.051–0.127	General applications flux or atmosphere
	0.000–0.002	0.000–0.051	Free flowing types, atmosphere brazing

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Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 309, Table 8.9, 1993, with permission of Elsevier Science, Burlington, MA.

(i.e., entrapped gas pockets), unbrazed areas, pores or porosity (i.e., from evolved or absorbed gases), flux inclusions, hot (solidification) cracks, shrinkage cracks, and brittle (often intermetallic) compounds. One of the most effective ways of preventing defects of these types is to properly place filler. Figure 7.12 shows how filler can be preplaced for maximum effectiveness, using various filler forms. Braze filler (whether applied during brazing or preplaced, and whether the process is performed manually or automatically) should be applied to the joint in such a way that when it melts and flows through the joint properly by capillary action, filler will appear at some point remote from the point of application. This technique relies on the sweeping action of the filler under the influence of the capillary forces and is a reasonable sign that proper flow and fill occurred.

SUMMARY

Brazing is a process for producing permanent, mechanically acceptable, leaktight joints comparable to fusion welding, but without necessitating melting of the base materials. It is accomplished by using a filler material that melts above 450°C (840°F) but below the solidus of the substrate materials, and that flows by capillary action into a properly designed joint consisting of a controlled gap or clearance. Wetting of the substrate surfaces by the filler is critical to the process, as it enables capillary flow and proper distribution. Joint strength is achieved through the formation of primary bonds: metallic bonds between metals with a metal filler; ionic, covalent, or mixed ionic–covalent

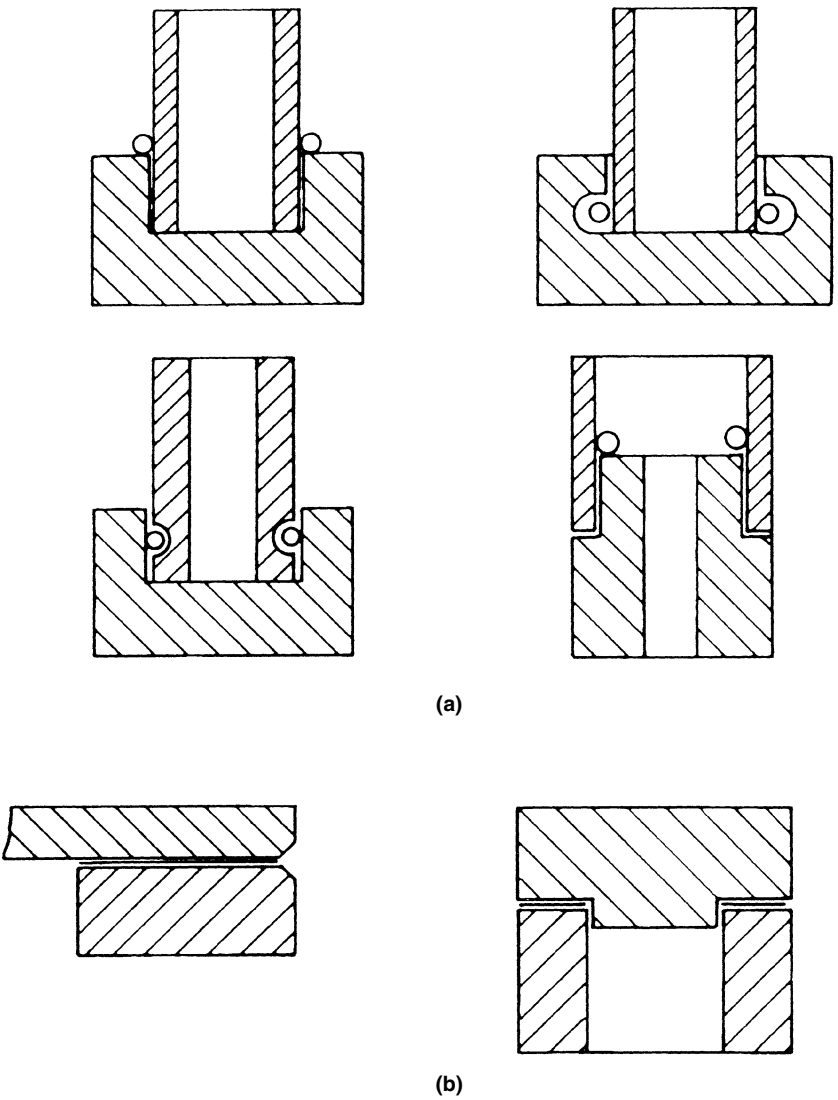

Figure 7.12 Schematic illustration of suggested approaches to preplacement of braze filler. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Figure 8.7, page 310, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

bonds between ceramics using either a metal or a ceramic filler; and ionic, covalent, or mixed ionic–covalent bonds between a metal and a ceramic using a metal filler.

Brazing is capable of producing strong, continuous joints over large areas or long lengths with little or no alteration of the microstructure or chemistry of the substrates. This allows dissimilar materials, by type or composition within a type, to

be readily joined. The surface bonding mechanism spreads loading, so thin and thick sections can be joined in any combination, under relatively stress-free conditions, producing close-tolerance structures or brazements. The most serious limitation of brazing can be service temperature because of the relatively low melting point of the fillers versus the base materials. This can be overcome, however, with proper filler choice or the use of a special diffusion process.

A variety of brazing process embodiments allows either manual or automatic operation with either localized heating of the joint or general, uniform heating of the entire braze assembly. Classification of processes is normally by the method of heating, with examples being torch brazing, furnace brazing, induction brazing, resistance brazing, dip brazing, infrared brazing, and laser or electron-beam brazing. Other special processes not classified by heating method include diffusion brazing, ultrasonically assisted brazing, and step-brazing.

Braze filler can be metallic or ceramic. Metallic fillers are used for joining metals or ceramics to themselves or to one another, while ceramic fillers are used exclusively for joining ceramics. Important characteristics of brazing filler materials are chemical, mechanical, and physical compatibility with the base materials, melting temperature and fluidity, tendency for liquid and solid phases to separate or liquate, and the ability to wet and bond the substrates. Typically, braze filler alloys exhibit a low melting eutectic constituent in their constitutional diagram.

It is critical to avoid oxidation of heated metal substrates and molten metal fillers throughout brazing, so a chemically reducing non-metallic flux or inert or reducing gaseous atmosphere or vacuum is usually used. Joint design for brazements can be in the lap, butt, or scarf configurations and must have controlled clearances during actual brazing to ensure proper flow of filler and filler thickness. If the filler layer is too thin, strain across the joint cannot be accommodated without fracture, while if it is too thick, plastic flow occurs and the joint is weakened. Joint clearance and filler placement are two important factors in preventing formation of defects during brazing.

QUESTIONS AND PROBLEMS

1. Differentiate the process of *brazing* from (a) fusion welding, (b) non-fusion welding, and (c) soldering.
2. What are the specific advantages of brazing versus fusion welding? What are the specific advantages of brazing versus mechanical fastening or integral attachment? What are the specific advantages of brazing versus adhesive bonding?
3. What is the single greatest limitation of brazing as a joining process compared to fusion welding? What about compared to adhesive bonding? What about compared to mechanical joining?
4. Which specific brazing processes require the entire assembly to be heated to the brazing temperature? What are some disadvantages of such processes?
5. What is the particular advantage of the induction brazing process that makes it so popular in industry? What is a particular limitation? What is the particular advantage of infrared brazing? What is a particular limitation? How are these processes similar and how are they different?

6. How does diffusion brazing differ from all other brazing processes? What are some particular advantages of the diffusion brazing process?
7. What is "step brazing"? Cite an example in a typical production or repair scenario where step brazing would be useful.
8. What is considered a suitable melting range for a braze filler for a particular base metal alloy? Is a wide melting temperature range for a braze filler alloy considered advantageous or disadvantageous? Explain.
9. Cite an example of when it would be considered advantageous for a braze filler alloy to react with the substrate material(s). Cite an example of when it would be considered disadvantageous for such a reaction to occur.
10. What factors, other than base metal melting point, determine what the melting temperature range should be for brazing a particular material combination? What are some particular manufacturing concerns related to the temperature required to accomplish brazing?
11. Which AWS class of brazing alloy filler would you select for each of the following?
    a. Maximum temperature serviceability
    b. Maximum general corrosion resistance
    c. Optimum suitability for high vacuum seals
    d. Optimum electrical conductivity
    e. Joining aluminum alloys

    Support your choice in each case with actual pertinent property data.
12. Differentiate between the roles of all chemical fluxes used for brazing versus most controlled atmospheres. What is one of the most significant factors affecting the oxidizing potential of a furnace atmosphere?
13. Compare the design of joints that are to be brazed to (a) typical fusion welding joints and (b) typical adhesive-bonding joints.
14. What would you expect to be the various failure modes observed in brazed joints? Explain.
15. Why is the gap, or clearance, of a braze joint important? How is the gap established and maintained during production brazing?

Bonus Problems:

A. Why is it that heat from a source in brazing (and in soldering) is always applied to the part(s) to be brazed (or soldered) rather than to the braze filler as with, say, a wire? What difference does it make as long as the substrate is not supposed to melt anyway?

B. Find a binary alloy system in which transient liquid-phase bonding is performed and, using the appropriate phase diagram, explain, step by step, as time progresses, what happens that leads to joint formation.

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Chapter 8

Soldering: A Subset of Brazing

8.1 INTRODUCTION TO THE PROCESS OF SOLDERING

Pure and alloyed metals and ceramics can be joined by causing a molten material to flow to fill the space between closely gapped joint faces and then solidify without requiring or causing melting in the base materials. One process, described in Chapter 7, is brazing; the other, to be described here, is *soldering*. In both cases the process of filling occurs by capillary action due to wetting of the solid substrate(s) by the molten filler and spreading of the molten filler by the lowering of surface free energy. Brazing and soldering are distinguished from adhesive bonding, which also uses filler that can be in a liquid form, by the nature of the filler and the filler's distribution to and within the joint. Brazes and solders are always inorganic and are usually metallic, while adhesives are almost always organic and, even when they are inorganic, are never metallic.[1] Both braze and solder fillers flow into and fill the joint by capillary action. Adhesives are usually applied to the faying surfaces to be bonded and do not depend upon capillary flow for their distribution within the joint. Brazing and soldering are distinguished from one another primarily on the basis of the melting temperatures of their fillers. Braze fillers melt above 450°C (840°F), while solder fillers or solders melt below this temperature, which was established by convention.

The forces responsible for joining in soldering arise from the formation of bonds[2] between the filler and the substrate or substrates, but there is often a significant contribution from a purely mechanical component as a result of interlocking between the wetting solder and microscopic asperities on the substrate's surface. As a result of lower adhesion and the lower strength of solder alloys themselves, soldered joints are generally less strong than brazed joints. While soldering was used by ancient civilizations for joining metals as far back as the Bronze Age, this was a simple process primarily because of the low melting temperatures of the fillers and the low heat requirement. In modern times, soldering is used predominantly to provide electrical

[1] Solders are always metals, although there are so-called *solder glasses*, which will be described in Chapter 12. Solder glasses are simply low-melting glasses used to join other glasses, or possibly ceramics containing a glassy phase.

[2] The bonds formed between a solder and a substrate depend on the substrate but are almost always metallic. This is true when the substrates are metals and often when they are ceramics. When the substrate is a glass, bonding between either a metallic or a glass solder can be covalent or, more likely, van der Waal's.

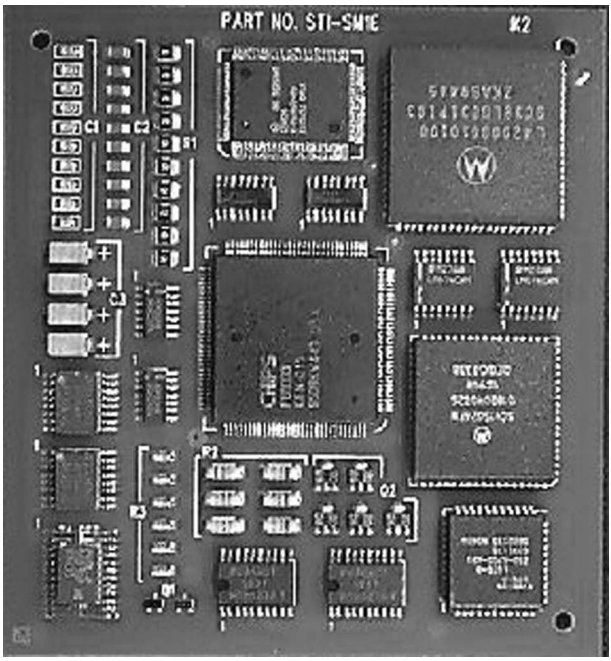

Figure 8.1 A typical application of the mass soldering of many joints, simultaneously, in a modern printed wire board assembly. (Courtesy of Sandia National Laboratories, with permission.)

continuity and conductivity (i.e., connectivity) and/or hermeticity.[3] Sound, conductive, and hermetically tight joints can be formed at low temperatures with little or no thermal degradation of the base materials. Because of these attributes, soldering has been and continues to be an extremely important process for joining electrical and electronic components. Figure 8.1 shows a typical example of the use of soldering in the pervasive and growing electronics industry.

This chapter looks at the process of soldering for joining. First, the process of soldering is defined, and its relative advantages and disadvantages are compared to other joining processes. Then, the principles of operation of soldering are discussed, and important individual soldering process embodiments are presented. Next, the metallurgy of solders is presented in some detail for the representative and predominant tin-lead system of solders, and as overviews for important but less-often-used systems. The physical forms of solders are then described. The critical role of fluxes, their compositions, and their physical forms are then described. Next, solder joint design is presented. Finally, methods for evaluating the solderability of materials are addressed.

[3] *Hermeticity* is the property of being sealed completely against the escape or entry of a gas, liquid, or vacuum.

8.2 SOLDERING AS A JOINING PROCESS AND SUBSET OF BRAZING

8.2.1 General Description of Soldering

Soldering is defined as a subclassification of welding that produces coalescence of materials by heating them to a suitable temperature and by using a filler material having a liquidus temperature not exceeding 450°C (840°F) and remaining below the solidus temperature of the lowest melting base material with which it is used. The filler material used in soldering, called a "solder," is a low-melting metal (e.g., Pb, Sn, Zn, or In) or metallic alloy, regardless of whether the base materials being joined to themselves or to one another are metals, ceramics, intermetallics, or glasses. The molten filler flows into and fills a pre-prepared (i.e., cleaned and gapped) joint between base materials by capillary action. The filler must wet the substrates, and it spreads by lowering the surface free energy of those substrates and their interface to the surroundings, often through a chemical reaction. So-called "solder glasses" are low-melting glasses that are used for joining one glass to another or to a metal, but these are not truly solders because they do not flow by capillary action, as they are usually far too viscous to do so.

The bond formed between a solder and base materials is almost always a combination of chemical bond formation and mechanical interlocking of the solder into microscopic "hills and valleys" (asperities) on the base materials' surfaces. An essential feature of soldered joints is that bonds are produced by a solvent action. Ideally, the solder dissolves, but does not melt, a small amount of the base material to form a layer of intermetallic compound through chemical reaction. This inherently brittle[4] layer often limits the strength (really the tolerance for strain that can be developed) but facilitates the spreading and adhesion of the solder. The ease with which this essential solvent action occurs is directly related to the ease of wetting of the substrate by the molten solder and is described as the "solderability" of the base material. Until fairly recently (perhaps the last 20 years), the role of such partial dissolution, compound formation, and formation of actual metallurgical bonds was not well known. The adhesion of solders was attributed virtually entirely to mechanical interlocking.[5]

While the mechanical integrity of soldered joints is limited compared to other welding and brazing processes, electrical continuity (or "connectivity") and leaktightness (or "hermeticity") is excellent. For these reasons, soldering is most important for the joining or interconnection of electrical components in electrical or electronic devices and assemblies. A standard radio receiver contains about 500 soldered joints;

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[4] Intermetallic compounds tend to be inherently brittle because they have crystal structures that are ordered (i.e., specific atomic species comprising the compound occupy specific, equivalent lattice sites). As an example, in the intermetallic compound Ni_3Al, all of the Ni atoms occupy lattice sites at the center of the faces of a cube, while all Al atoms occupy lattice sites at the corners of that cube. Any attempt to deform such a crystal by slip would disrupt this order, which is resisted due to the energetic penalty. Thus, fracture by cleavage is favored over deformation by slip, hence the high strength of such materials.

[5] This lack of knowledge stemmed from the most common solders being handed down over centuries of use, with little need or motivation to understand precisely how these important alloys worked to create adhesion. Pressure to find alternatives to Pb-containing solders to preclude environmental problems due to Pb's toxicity led to extensive research into existing systems to understand what was needed in replacement systems.

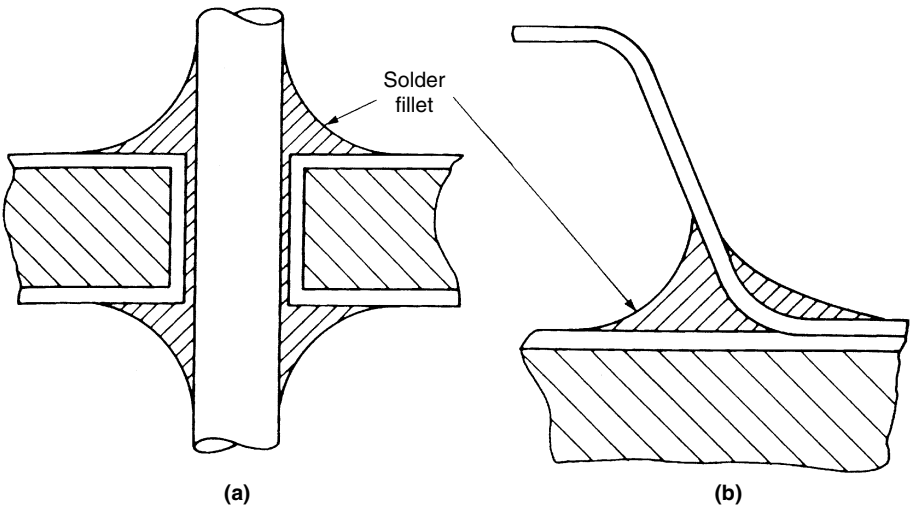

Figure 8.2 Schematic illustrations of typical solder joints showing the natural self-formation of a fillet by wetting to reduce stress concentration with (a) through-hole lead and (b) preformed lead in surface-mount technology. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 9.2, page 317, Butterworth-Heinemann, Stoneham, MA, with permission of Elsevier Science, Burlington, MA.)

a large-screen TV contains about 5,000 soldered joints; and a computer or telephone switching system contains 100,000 to more than 1,000,000 soldered joints. With the correct joint design and application of a good process, reliable joints are obtained, having negligible contact resistance and acceptable strength. Reliability implies that the joints have the desired properties immediately after production and can be depended upon to provide failure-free performance during the life of the equipment.

Figure 8.2 schematically illustrates typical soldered joints using (a) through-hole and (b) surface-mount technology.

8.2.2 Soldering Compared to Non-Fusion Welding, Brazing, and Adhesive Bonding

Soldering, brazing, and adhesive bonding are all processes that are capable of forming a joint between base materials by forming chemical bonds between an intermediary and the base materials without requiring or causing any melting or, hence, serious degradation of those base materials. While non-fusion welding processes (see Chapter 6, Section 6.5) are also capable of forming such joints, bonding is direct for these processes (requiring no intermediary) and joint strength arises for the formation of primary bonds due to the atomic-level physical forces. Atoms, ions, or molecules of the base materials are brought into contact to their equilibrium spacing under the action of pressure, with or without bulk heating. No filler material or intermediary is needed or used. In soldering, brazing, and adhesive bonding, bonding is accomplished through

an intermediary. The intermediary is added to provide a source of atoms, ions, or molecules to allow bonding of the base materials through the intermediary. Pressure beyond that needed to hold the joint elements in contact is usually not required and is almost never applied. The intermediary is called a "filler material" or "filler alloy" for brazing or a "solder" for soldering. For adhesive bonding, the intermediary is called an "adhesive." Here, the similarity between the processes breaks down.

Both brazing and soldering require that the filler melt, flow into, and fill the joint by surface wetting and capillary action. In adhesive bonding, there is no such requirement of the adhesive. First, the adhesives used for adhesive bonding melt only if they are thermoplastic polymers; otherwise, they start out as liquids before they cure (in the case of thermosetting polymers and most inorganic adhesives, including cement) or dry by evaporation and/or absorption (in the case of solvent-thinned thermoplastics). Also, capillary action is only rarely involved in the distribution of certain liquid adhesives. More often, adhesives are applied to the faying surfaces of the parts to be joined so that distribution of the adhesive is accomplished as a step in the preparation process (i.e., adhesive application). The composition of the intermediaries used with soldering and brazing versus adhesive bonding also differ considerably. Braze and solder fillers are always alloys of inorganic materials. Braze fillers can be alloys of metals or ceramics, while solders can be alloys of metals or pure, low-melting metals (e.g., In, Pb, Sn, or Zn), except in the case of "solder glasses" (see Chapter 12, Subsection 12.8.4). Adhesives, on the other hand, are usually organic materials (e.g., resins) but can be inorganic compounds (e.g., sodium silicate) or mixtures of such compounds (e.g., various cements and mortars).

The bonding that develops between the intermediary and the base material(s) is often primary for soldering and brazing, while it is usually secondary for adhesive bonding. The source of the strength of joints produced by brazing, however, comes entirely from these primary bonds, while for soldering, as for adhesive bonding, a significant and sometimes dominant portion of the strength arises from purely mechanical sources. As with adhesives in adhesive bonding, solders fill the microscopic valleys always found on real surfaces of base materials through wetting and, by so doing, mechanically lock the substrate to the adhesive or solder.

8.2.3 Advantages and Disadvantages of Soldering

Obviously, the low temperatures needed to accomplish soldering mean that base materials can be joined with little or no thermal damage in most cases. Besides this important general advantage, soldering has some specific advantages over competitive joining techniques like welding or adhesive bonding. First, the solder joint forms itself by the nature of the wetting process, even when the heat and solder are not directed precisely at the places to be soldered. The meniscus that forms upon wetting of the substrate by the molten solder automatically produces a joint that gives rise to minimal stress concentration (or "notch effect") under loading. This is shown in the schematic illustration of typical solder joints in Figure 8.2, where surface tension causes the molten solder to form a natural fillet or radius, rather than a sharp notch. Second, because most solders do not adhere to most insulating materials (e.g., polymers, ceramics, or glasses),

unless a special effort is made, it may, in many cases, be applied in excess quantities (even using immersion) without detriment (e.g., short circuits from bridging between physically separated, and supposedly electrically isolated, joints). This enables mass soldering of joints, another distinct advantage in achieving high manufacturing productivity, especially where very large numbers of joints are involved in each assembly to be soldered. Third, as the soldering temperature is relatively low, there is no need for the heat to be applied locally as for welding. Rather, the entire assembly can usually be heated to a suitable temperature to allow soldering without detriment. In situations where the entire assembly cannot be heated to the soldering temperature, local heating is still easily accomplished by a number of approaches using simple heating devices.

A fourth advantage is that soldering allows considerable freedom in the dimensioning of joints. Because of this it is possible to obtain good results even if a large variety of components is used on the same general assembly without having to adjust process parameters for each particular type of joint. Fifth, the equipment needed for both manual (i.e., hand) soldering and machine soldering is relatively simple, and the process can be easily automated, thereby offering production economies (e.g., in-line processing). A sixth rather unique advantage, shared completely only by mechanical fastening and some forms of integral attachment and occasionally by adhesive bonding, is that soldered connections can be disassembled without damaging the materials or parts involved (i.e., "de-soldered"). This makes repair and/or upgrade easy to accomplish.

The adoption of mechanized methods for soldering, in particular, and for manufacturing, in general, is stimulated on the one hand by considerations of efficiency and on the other hand by the desire to obtain a more closely controlled quality than is realized by manual techniques for most products. This all means improved productivity. Machine soldering affords a gain in quality because the machine, unlike a human being, never relaxes its attention and never tires. At the same time, however, machine soldering almost inevitably involves losses because the process is generally incapable of adapting to extreme or unexpected situations. Unless special measures are taken (e.g., elaborate sensing and adaptive or intelligent control schemes), no automated methods are able to cope with such contingencies as inadequate solderability of certain joints or deficiencies in the soldering process.

The principal disadvantage of soldering is that the strength of a soldered joint (and particularly the strength under mechanical or thermally induced fatigue) is quite limited compared to other joining methods such as welding, brazing, and even adhesive bonding. The creep strength of soldered joints is also inferior to welded or brazed joints because of the lower melting point of the filler and the correspondingly higher homologous temperature imposed on the joint. To show how serious this can be, room temperature (i.e., 25°C or 298°K, which is 77°F) is 65% of the absolute melting temperature of the most commonly used eutectic Sn–Pb solder (i.e., 183°C or 456°K, which is 288°F), well into the range where creep can be expected in metals (typically, 50–60% of $T_{MP,\ absolute}$). Typical operating temperatures of electronic devices under the hood of an automobile, for example, can easily cause Sn–Pb eutectic solders to operate at 90% of the homologous temperature. No materials engineer would risk running a gas turbine jet engine at homologous temperatures like that, so why should electrical engineers run solder joints there?

Table 8.1 Advantages and Disadvantages of Soldering Versus Other Joining Processes

Advantages	*Disadvantages*
• Solder joints form themselves by the nature of the wetting process; joint formation is self-controlling • Process is amenable to producing many joints at once, *en masse* • Heat need not be applied locally to preclude heat effects in base materials • Almost no significant change in microstructure or composition of base materials • There is considerable freedom in joint dimensioning • Process is amenable to automation, but can be performed manually • Process allows disassembly by "de-soldering," unique among welding processes	• Strength is very limited, as low-melting alloys are inherently of low strength • Low melting temperatures mean service is usually at high homologous temperatures, so creep is a problem • Uniform heating of the entire assembly by some soldering processes can be detrimental to heat-sensitive components • Production of multiple joints *en masse* can make inspection of every joint difficult or impractical and places high demands on process control • Microstructure often evolves considerably at high homologous temperatures or due to cycling temperatures

A practical difference between soldering and welding is that in welding the welds almost always have to be made consecutively, whereas soldered joints can be made simultaneously in one operation. This factor, in principle, makes soldering a cheap joining method. On the other hand, ensuring the quality of every joint becomes essential, and is difficult and demands either expensive, off-line, post-process inspection or, in most modern operations, embedded quality assurance.

Table 8.1 summarizes the relative advantages and disadvantages of soldering versus other joining processes.

8.3 SOLDERING PROCESS CONSIDERATIONS

8.3.1 General Description of the Needs for Proper Soldering

Good-quality solder joints are obtained by selecting and using proper materials, processes, joint designs, and procedures. Key factors include (1) base material selection, (2) solder selection, (3) flux selection, (4) joint design, (5) part and joint precleaning, (6) soldering process selection and operation, (7) flux residue removal, and (8) joint inspection.

8.3.2 Base Material Considerations

Base materials are usually selected for the specific property requirements that are needed for the components' or assemblies intended function, such as strength, ductility,

electrical conductivity, thermal conductivity, weight, corrosion resistance, or vacuum compatibility. When soldering is required to join components, the solderability of the base material(s) must also be considered in their selection. The "solderability" of a material can vary widely and depends directly on the ease or difficulty of wetting, or "wettability." Table 8.2 lists metallic materials in terms of their wettability in the uncoated condition when a common Sn-Pb eutectic solder is used. There is a reasonably clear relationship between the wettability of a base metal by a solder and the tendency of that base metal to form a tenacious oxide. Some metals, like Cr and Mg, form tenacious oxides so readily that they are practically impossible to solder. Others, like Au, have very good wettability because they do not form oxides under most conditions. Still others form oxides, but these oxides can be easily removed.

Solderability or wettability can be enhanced by removing any oxide layer with an appropriate flux. For materials with inherently good wettability, mild or mildly aggressive fluxes can be used. For materials that are difficult to wet, very aggressive fluxes are required. For materials that are considered practically unwettable, coatings are required to serve as intermediaries to the solder. For many materials, removing the oxide as a processing step well before actual soldering must be followed by keeping the oxide from reforming up to the time of actual soldering. This is usually accomplished with coatings.

Figure 8.3 schematically illustrates the difference in wetting of a clean versus an oxidized base metal by a drop of molten solder. When the base metal is clean, the drop spreads and some diffusion occurs at the interface.[6] To be truly solderable, a material must be wettable and remain wettable even after some storage. If the wettability deteriorates during storage, the surface is said to "age."[7] Such aging is problematic in a production environment, as precleaning and soldering operations must be carefully timed.

Table 8.2 Ratings of the Wettability of Various Uncoated Materials by Eutectic Tin–Lead (Sn–Pb) Solder

Good	*Fair*	*Moderate*	*Difficult*	*Practically Impossible*
Gold	Bronzes	Kovar	Aluminum bronze	Chromium
Tin–Lead	Brasses	Nickel–iron	Alloyed steels	Magnesium
Tin	Monel	Nickel	Aluminum	Molybdenum
Silver	Nickel silver	Mild steels	Stainless steels	Tungsten
Palladium		Zinc		Beryllium
Mild flux ..... → ..... Aggressive flux				

[6] The diffusion that occurs at the interface between a clean base metal and a molten solder often results in the formation of a brittle intermetallic compound layer. This layer may limit the strength of the joint (just as a weak boundary layer limits the strength of an adhesive-bonded joint) but is believed to play an important role in the spreading and adhesion of the solder.

[7] The phenomenon of aging as it pertains to a surface prepared for soldering does not involve the same mechanism as the aging responsible for strengthening a precipitation-hardenable alloy. In soldering, aging involves the re-oxidation of the surface to be soldered.

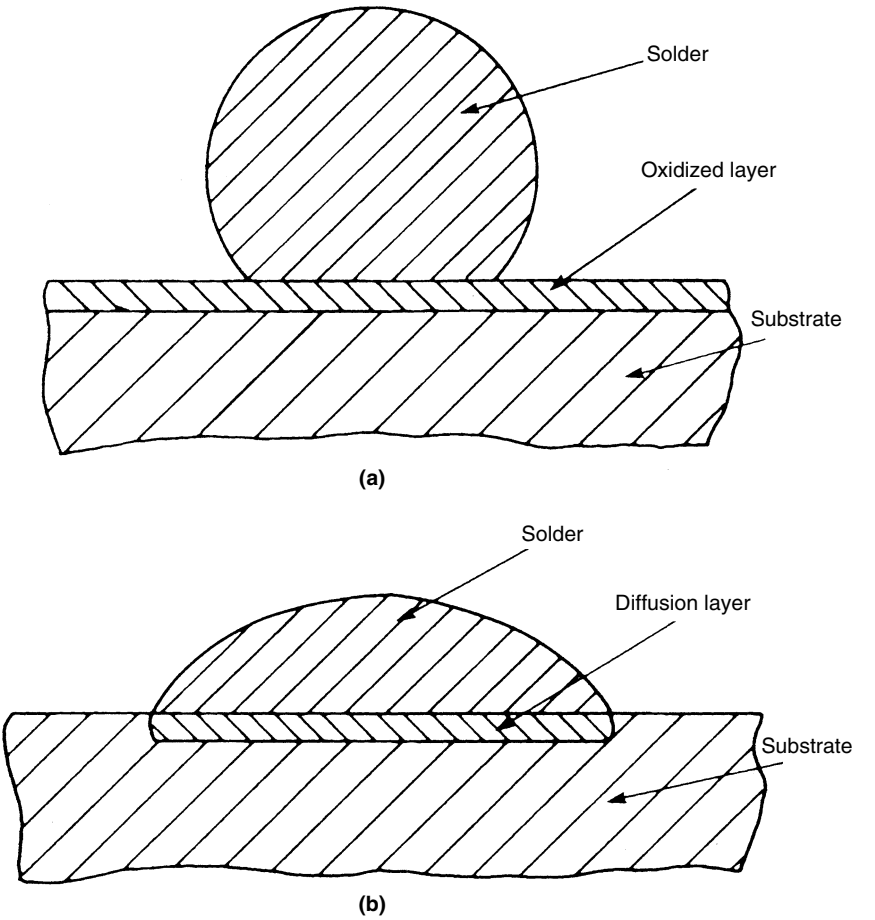

Figure 8.3 Schematic illustration of the difference in wetting of a clean (b) versus an oxidized (a) base metal by a drop of molten solder. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 9.3, page 320, Butterworth-Heinemann, Stoneham, MA, with permission of Elsevier Science, Burlington, MA.)

Base materials, whether metallic or not, may be coated for several reasons. These include decorative, protective, and functional purposes, as well as improving wettability for soldering. Coatings can provide protection against the environment or can improve function by increasing wear resistance, providing high reflectivity or specularity, or providing electrical contact or insulation, as desired. Coatings for improving solderability can be applied by electrolytic deposition, thermal deposition, mechanical cladding, physical vapor deposition, or chemical deposition. Different coating methods and systems are used for different purposes.

In addition to being used to enable soldering of normally unsolderable base materials, intermediate layers are sometimes used during soldering to provide (1) improved adhesion; (2) a barrier against the formation of brittle intermetallics; (3) a

barrier against zinc diffusion in zinc-bearing alloys (to prevent "dezincification"); and (4) improved corrosion resistance.

There are two other considerations in selecting base metals for solder joints. First, the materials making up the joint elements as well as the solder alloy must be electro-chemically compatible to avoid galvanic corrosion. Large differences in electrochemical potential (i.e., electronegativity) will lead to more severe galvanic corrosion. Second, the metals comprising the soldered joint, and the solder alloy, should be compatible in terms of their relative coefficients of thermal expansion. Too great a difference in coefficients of thermal expansion (CTEs) can give rise to severe thermally induced stresses, leading to thermal fatigue. As a rule, CTEs should be kept as close as possible, not exceeding 10–15% difference between adjacent materials. Large differences in CTE between base metals can often be handled by using several intermediate materials—or layers of materials—with intermediate values of CTE.

8.3.3 Solder Alloy Selection

The solder to be used in a soldered joint is selected to provide good wetting, spreading or flow, and joint penetration in the actual soldering operation *and* the desired joint properties in the finished product. As mentioned earlier, all solders are pure metals or alloys. Major solder alloy systems and their metallurgy are described in some detail in Section 8.4.

Table 8.3 summarizes the choice of solder alloys for various base materials.

8.3.4 Solder Flux Selection

A flux is intended to enhance the wetting of the base material by the solder by removing tarnish films from precleaned surfaces and preventing the reformation of

Table 8.3 Choice of Solder Alloys for Various Base Materials (Based on Best Compatibility)

	Al	*Be*	*Brass*	*Bronze*	*Ceramics*	*Cu*	*Fe*	*Glass*	*Mg*	*Ni*	*Pb*	*Si*	*Sn*	*SS*	*Ti*	*Zn*
Sn–Pb			•	•		•	•			•	•		•			
Sn–Sb/			•	•		•	•			•	•		•			
Sn–Sb–Pb																
Sn–Ag/		•	•	•		•	•			•	•		•	•	•	
Sn–Pb–Ag																
Sn–Zn	•		•	•		•					•					•
Cd–Ag			•	•		•	•							•		
Cd–Zn	•															•
Zn–Al	•															•
Bi alloys			•	•		•	•				•		•	•		•
In alloys	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Au			•	•		•	•			•		•				
Ge–Al	•		•	•		•						•				

oxide or tarnish during the soldering operation. The selection of the type of flux usually depends on the ease with which a material can be soldered (i.e., its solderability or wettability). This, in turn, usually relates to the ease with which any oxide or tarnish can be removed by chemical reduction. The need to obtain an atomically clean base metal goes back to the nature of how a bond is formed by physical forces in welding in the first place.

Chemically nonaggressive or mild fluxes are used with solderable base metals or metals that are precoated with a solderable finish. Rosins are naturally occurring resins derived from certain trees. Strong, chemically aggressive inorganic fluxes are usually used on metals that are difficult to wet, like stainless steels because of their Cr content. These are usually acids or salts of various types. Table 8.4 summarizes the flux requirements for various metals, alloys, and coatings.

8.3.5 Soldering Atmospheres

In lieu of fluxes, either inert or even chemically reducing gaseous atmospheres can be used to clean and subsequently protect precleaned joint elements in an assembly to be soldered.

Specific details of fluxes and atmospheres will be given in Section 8.6.

8.3.6 Solder Joint Design

Joints that are to be soldered should be designed to fulfill the requirements of the finished assembly and to permit application of flux and solder by the soldering process to be used. Joints should be designed so that proper clearance is maintained between joint elements during the heating and cooling stages of the soldering operation so that capillary flow can take place properly.

To maintain alignment of joint components during soldering, special fixtures may be necessary or the units of the assembly can be crimped, clinched, wrapped, or otherwise held together mechanically or by ''holding'' adhesives. Mechanical crimping and clinching actually enhances the joint's final strength by contributing mechanical forces to the physical bonding forces and, in many cases, are the predominant contributors to joint strength. Details of joint design are discussed in Section 8.7.

8.3.7 Precleaning

An unclean surface will prevent the molten solder from wetting and spreading, making soldering difficult or impossible and contributing to poor joint properties. All metal surfaces to be soldered should be cleaned before assembly to facilitate wetting of the base metal by the solder. Flux should not be considered a substitute for precleaning. Precleaning is necessary to remove organic contaminants like grease, oil, paint, pencil marks, lubricants, coolants, and dirt, as well as inorganic films like oxides and other tarnish

Table 8.4 Summary of Flux Requirements for Various Metals, Alloys, and Coatings

Base Metal, Alloy, or Applied Finish	*Flux Type*				*Soldering Not Recommended* [a]
	Rosin	*Organic*	*Inorganic*	*Special Flux and/or Solder*	
Aluminum	–	–	–	X	–
Aluminum–bronze	–	–	–	X	–
Beryllium	–	–	–	–	X
Beryllium–copper	X	X	X	–	–
Brass	X	X	X	–	–
Cadmium	X	X	X	–	–
Cast iron	–	–	–	X	–
Chromium	–	–	–	–	X
Copper	X	X	X	–	–
Copper–chromium	–	–	X	–	–
Copper–nickel	X	X	X	–	–
Copper–silicon	–	–	X	–	–
Gold	X	X	X	–	–
Inconel	–	–	–	X	–
Lead	X	X	X	–	–
Magnesium	–	–	–	–	X
Manganese–bronze (high tensile)	–	–	–	–	X
Monel	–	X	X	–	–
Nickel	–	X	X	–	–
Nickel–iron	–	X	X	–	–
Nichrome	–	–	–	X	–
Palladium	X	X	X	–	–
Platinum	X	X	X	–	–
Rhodium	–	–	X	–	–
Silver	X	X	X	–	–
Stainless steel	–	X	X	–	–
Steel	–	–	X	–	–
Tin	X	X	X	–	–
Tin–bronze	X	X	X	–	–
Tin–lead	X	X	X	–	–
Tin–nickel	–	X	X	–	–
Tin–zinc	X	X	X	–	–
Titanium	–	–	–	–	X
Zinc	–	X	X	–	–
Zinc die castings	–	–	–	–	X

[a]With proper procedures, such as precoating, most metals can be soldered.
Reprinted with permission from *Welding Handbook*, Vol. 2, 8th ed, Miami, FL, American Welding Society, page 426, 1991, with permission.

layers. The goal of precleaning is to expose the atomically clean base metal to the molten solder, and the importance of proper precleaning in soldering, as well as in welding and brazing, cannot be overemphasized.

Precleaning can involve any or all of the following three progressively vigorous methods: (1) degreasing, (2) pickling, and (3) mechanical cleaning. Precleaning may also be followed by a fourth step, precoating. In degreasing, organic contaminants such as oil and grease, and loosely adhering inorganic contaminants such as dirt, are removed using either solvents or alkaline solutions. Methods are generally similar to those used for degreasing before adhesive bonding (see Chapter 4, Subsection 4.5.2). Back deposition of residue must be avoided by proper cleaning methods and rinsing. All cleaning solutions should be thoroughly removed before soldering, by any process.

If the base metals to be soldered have tenacious layers of organic contaminants or inorganic films of rust, scale, oxides, or other films, these can be removed by acid cleaning or "pickling." Inorganic acids such as hydrochloric, sulfuric, phosphoric, nitric, and hydrofluoric, singly or in combination, can be used. After pickling, parts should be washed in hot water and dried as quickly as possible to stop the action of the acid and remove reaction residues.

Mechanical cleaning may be needed to remove tenacious oxides or other films and to roughen the joint surfaces to improve adhesion through mechanical interlocking. Methods include grit or shot blasting, mechanical sanding, filing or hand sanding, cleaning with steel wool, and wire brushing or scraping. Mechanical cleaning should be avoided on soft base metals like Cu, and care should always be exercised to avoid entrapment of cleaning and cleaner residue.

Precoating may be necessary for metals that are difficult to solder because they oxidize readily and, thus, can re-oxidize after precleaning if soldering is delayed too long. Precoating involves coating the base metal surfaces to be soldered with a more solderable and more oxidation-resistant metal or alloy before the soldering operation. Tin, copper, silver, cadmium, iron, nickel, and alloys of Sn–Pb, Sn–Zn, Sn–Cu, and Sn–Ni are used as precoats. Sometimes precoating is called "tinning" or "pretinning," even when Sn is not a component of the precoating material. Precoating is essentially mandatory for metals with tenacious oxides (e.g., Al, Al–bronze, highly alloyed steels, and cast iron). Precoating produces such advantages as more rapid and uniform soldering and the ability to avoid using strong acid fluxes.

8.3.8 Choice of Soldering Process

The soldering process should be selected to provide the proper soldering temperature, heat distribution, and rate of heating and cooling required for the product to be properly assembled. The number of joints to be soldered (i.e., production volumes and rates), as well as the joint quality requirements, also influence the process selection. The most important soldering processes are described in Section 8.6.

The specific method for applying the solder and the flux will be dictated by the selection of the soldering process.

8.3.9 Excess Solder and Flux Residue Removal

Generally, flux residues should be thoroughly removed after soldering, since such residues are almost always corrosive. The more active the flux, the more important the rapid and complete removal of flux residue becomes. These residues, or their corrosion products, can also degrade electrical properties by contaminating contacting surfaces. Excess solder in the form of solder spatter or "solder balls" must also be removed, as these can break loose, become trapped at electrical contacts or between circuit paths, and cause electrical shorts. Obviously, solder bridges across circuit paths (i.e., "bridges") must be removed because they produce electrical short circuits.

Flux residue can usually be removed with hot or warm water (often with sodium carbonate added) but may require organic solvents to hasten dissolution and/or avoid water damage immediately or due to entrapment. This is a particular concern in electronic assemblies. Ultrasonic assist can facilitate residue removal. Excess solder must usually be removed mechanically.

A growing concern is the traditional use of chlorinated hydrocarbon or chlorofluorocarbon (CFC) solvents, as these are known to cause adverse environmental effects (e.g., ozone depletion in the atmosphere). Non-chlorinated or non-chlorofluoro types are being sought.

8.4 SOLDERING PROCESSES

8.4.1 General Description of Soldering Processes

The proper application of heat is of paramount importance during any soldering operation, as it is during fusion welding and brazing. In the case of soldering, the heat should be applied in such a manner that the solder melts while the surfaces to be soldered are heated to permit the molten solder to wet and flow over the surfaces. Heating can be done manually or by machine, semi-automatically or automatically, locally at the joint or uniformly over the entire assembly, and using any of many sources. Table 8.5 classifies soldering processes.

The following subsections briefly describe some of the more important soldering processes. Much more comprehensive descriptions are available in the American Welding Society's *Soldering Manual* (2000).

8.4.2 Iron Soldering

Iron soldering is a traditional manual process that uses a copper tip that is heated by electric resistance, gas, or oil. This, in turn, heats the local area to be soldered near the point of solder application. The selection of soldering irons can be simplified by classifying them into four groups, as follows: (1) soldering irons for service or repair; (2) transformer-type, low-voltage, pencil-type irons; (3) special quick-heating or plier-type irons; and (4) heavy-duty industrial irons. Regardless of the heating method, the tip performs several important functions. It stores and conducts heat from the heat

Table 8.5 Classification of Soldering Processes

Chemical Processes	
Based on combustion	Torch soldering
Based on condensation	Iron soldering (flame heated)
Based on non-electrolytic deposition	Condensation soldering or Vapor phase
Based on bath immersion	reflow soldering
Based on spraying	Deposition soldering
	Chemical dip soldering
	Molten metal dip soldering
	Wave (or cascade) soldering
	Spray soldering
Electrical Processes	
Based on heat conduction	Oven soldering
Based on current induction	Hot gas soldering
Based on heat radiation	Induction soldering
Based on resistance	Infrared soldering
	Iron soldering
	Resistance soldering
Mechanical Processes	
Enabled by abrasion	Active soldering
Aided by vibration	Ultrasonic soldering

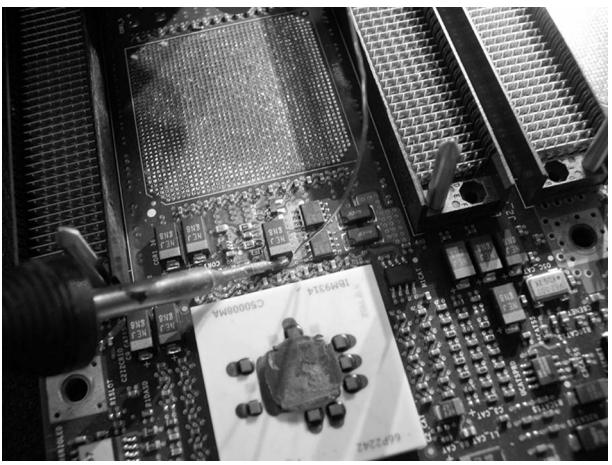

Figure 8.4 Typical use of manual iron soldering in industry. (Courtesy of the IBM Corporation, Poughkeepsie, NY, with permission.)

source to the part(s) to be soldered; it stores molten solder (through wetting and adhesion to the tip); it conveys the molten solder; and it withdraws surplus molten solder from the joint area (also through wetting of the tip). Iron soldering has the advantage of being inexpensive and highly portable, but it relies on operator skill and is slow.

Figure 8.4 shows an operator performing iron soldering.

8.4.3 Torch Soldering

In *torch soldering*, as in torch brazing, a combustion flame is used as the source of heat. Heating is usually localized but can be more general, raising the temperature of the entire assembly or a large portion of the assembly. The process can be, and often is, manual but can be automated. The selection of the torch is dictated by the size, mass, and configuration of the assembly to be soldered. The temperature of the torch flame and the heat intensity of the process depend on the gas or gases used. Lower temperatures are obtained with propane, butane, or natural or MAPP gas burned with atmospheric or pressurized air. Higher temperatures are obtained with acetylene burned with pressurized oxygen. The design of a soldering torch is essentially identical to that used for oxy-fuel gas welding and for torch brazing (see Chapter 6, Figure 6.10). As in welding and brazing, the fuel gas and air (or oxygen) mixture can be adjusted to render the flame oxidizing (with excess oxygen), neutral (when in proper molar ratio), or reducing (with insufficient oxygen). Proper gas adjustment should generally avoid a sooty flame, which is one starved for oxygen, as soot deposited on the part hinders wetting. Multiple flame tips or burners are often used for large or massive work, such as filling seams or dents in automobile bodies during their manufacture or repair, or for plumbing.

8.4.4 Oven Soldering

Oven soldering[8] is a good, high-production volume or rate process that should be considered when (1) the entire assembly can be brought to the soldering temperature without damage; (2) production volume or rate justifies the cost of fixtures for holding joint components together during soldering; and (3) the assembly is complicated, making other methods impractical. Only fluxes that do not decompose upon exposure to elevated temperature for some time can be used in oven soldering.

8.4.5 Dip Soldering

Dip soldering, analogous to molten metal dip brazing, uses a molten bath of solder to supply both the heat and the solder necessary to produce soldered joints. Heating is general to the entire assembly, which limits utility. The process is always automated and is, therefore, excellent for productivity, as many joints can be soldered at the same time. Figure 8.5 schematically illustrates the dip soldering process, as well as some other related soldering processes. There is a danger with dip soldering (as there is with dip brazing) of thermally shocking the assembly being joined, since heat is applied from a large heat source very suddenly. Obviously, all of the materials in an assembly to be dip soldered must be able to tolerate the soldering temperature, which always includes a superheat of 30–50°C (50–90°F) over the liquidus of the solder.

[8] The distinction between a "furnace" and an "oven" in manufacturing is ill defined but seems to absolutely related to the peak temperature that can be achieved and, secondarily, if at all, to the source of heat. Furnaces are capable of higher peak temperatures. Ovens tend to be gas fired and rely on convection for uniform temperature.

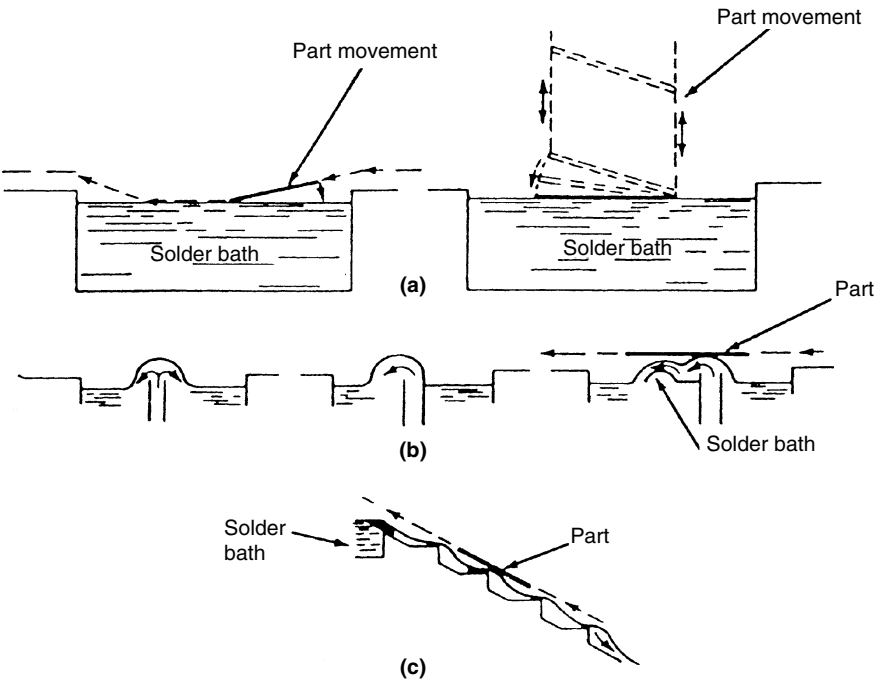

Figure 8.5 Schematic representations of (a) dip soldering, as well as other, closely related methods, including: (b) wave soldering and (c) cascade soldering. (Reprinted from *Welding Handbook*, 8th edition, Vol. 2, "Welding Processes," Fig. 13.6, page 443, American Welding Society, Miami, FL, 1991, with permission.)

8.4.6 Wave Soldering

In *wave soldering*, molten solder is pumped out of a narrow slit to produce a wave or series of waves on the surface of a bath of molten solder. These waves sweep over the assembly, which is suspended above the surface of the bath with just the joints close enough to be struck by the wave, providing both heat and solder. Wave soldering systems, such as those shown in Figures 8.5 and 8.6, provide a virtually oxide-free surface to the part by breaking any oxide skull on top of the bath with the wave motion. In addition, the waves act to sweep flux and vapors away after soldering. Heat tends to be localized at the surface of the assembly, at the joints to be soldered. Flux has to be preplaced before soldering. There are, in fact, several variations of wave soldering, including "lambda-wave" and "double-wave," with the principal differences being the form of the wave or waves.

8.4.7 Induction Soldering

The material to be soldered by the *induction soldering* process must be an electrical conductor. The rate of heating depends upon the induced current flow, while the

Figure 8.6 A typical facility for wave soldering electronic assemblies to achieve electrical interconnect en masse. (Courtesy of the IBM Corporation, Poughkeepsie, NY, with permission.)

distribution (especially, depth of penetration) of heat depends on the frequency. The higher the frequency, the more concentrated the heat is at the surface. Induction soldering is generally considered for (1) large-scale production (i.e., volume and rate); (2) application of heat to a localized area to prevent damage to surroundings; (3) minimum oxidation to surrounding areas; (4) good joint appearance and consistently high joint quality; and (5) simple joint designs, amenable to automation. Some additional details in induction heating are given in Chapter 7, Subsection 7.4.4, ''Induction Brazing.''

8.4.8 Resistance Soldering

In resistance soldering, the workpiece is placed between a ground and a movable electrode or between two moveable electrodes to complete an electrical circuit. Heat is applied locally to the joint area both by the electrical resistance of the metal being soldered and by conduction of heat from the electrode(s), which is (are) usually carbon. Solder must be fed into the joint during this process or, more often, is supplied by preplaced preforms or solder coatings (i.e., ''pretinning''). The process is a so-called ''reflow'' process (see Subsection 8.4.10) and is used for its accurate control of heat input, short heating cycle, and potentially highly localized heating. These are beneficial process attributes for certain, especially heat-sensitive materials or assemblies.

8.4.9 Other Special Soldering Methods

There are several other methods of supplying heat to a joint or array of joints to accomplish soldering. *Infrared soldering* focuses an infrared light source to accomplish heating very locally, in thin-section structures (see Subsection 7.4.6). Some newer

embodiments use the short-duration flash from an intense white light source, such as a xenon bulb, to accomplish soldering in essentially the same way. *Hot gas soldering* uses a fine jet of heated inert gas (e.g., nitrogen) for heating. *Ultrasonic soldering*, like ultrasonic brazing (Subsection 7.4.8) is really ultrasonically assisted dip soldering, where the ultrasonic energy breaks up tenacious oxides on the part or on the surface of the bath. Soldering can also be accomplished using spray guns for applying molten solder (i.e., in *spray soldering*). In *condensation soldering*, the latent heat of a condensing saturated vapor (usually of an organic solvent) provides heat for soldering. Many of these processes are used in so-called "reflow soldering," to be described next.

8.4.10 Reflow Methods of Soldering

In *reflow methods*, solder is predeposited at each joint as a preform, a paste, or a solder plating or coating. The solder is then melted in place, or "reflowed," by any one of several methods, including resistance, hot gas heating, forced air ovens, radiant (IR or white light) heating, liquid immersion, or vapor-phase condensation. More recently, lasers have been used for soldering by a reflow method, with the potential for melting solders with low or high melting temperatures or even for joining by microwelding without the need for solder. Lasers also may permit fluxless soldering by ablating away oxide layers via thermal shock.

8.5 SOLDERS AND BASIC SOLDER ALLOY METALLURGY

8.5.1 Basic Characteristics Required of Solders

Solders are usually alloys but occasionally are pure metals, with liquidus temperatures lower than 450°C (840°F) and with good fluidity, good wetting characteristics, reasonable strength, and, often, good electrical and thermal conductivity. To satisfy the requirement that liquidus temperatures be below 450°C, most solders are alloys of inherently low-melting metals, usually exhibiting a eutectic in their phase diagrams. Good fluidity is no problem with low-melting pure metals, since most metals are highly fluid above their melting point (typically having viscosities close to water), but fluidity of alloys depends on the relative proportions of liquid and solid phases in equilibrium at the temperature at which soldering takes place. Proper alloying, especially the use of ternary (third) alloying additions, influences the proportions of liquid and solid in equilibrium in a solder. Fluidity of alloys was discussed in Subsection 7.5.1.

The major alloy systems used for solders include (1) tin–lead (Sn–Pb), (2) tin–antimony (Sn–Sb), (3) tin–antimony–lead (Sn–Sb–Pb), (4) tin–silver (Sn–Ag) and tin–silver–lead (Sn–Ag–Pb), (5) tin-zinc (Sn–Zn), (6) cadmium–silver (Cd–Ag), (7) cadmium–zinc (Cd–Zn), (8) zinc-aluminum (Zn–Al), (9) bismuth–containing "fusible alloys," and (10) indium (In) alloys.

There is growing pressure to find effective Pb-free solders given the growing awareness of and concern for the toxicity of Pb and its polluting effects on the environment at every stage of its production, use, and disposal.

8.5.2 Tin–Lead Solders

Solders of the Sn–Pb binary alloy system constitute the largest proportion of all solders in use, now and ever. They are used for joining most metals and have good corrosion resistance to most media. Most cleaning and soldering processes can be used with Sn–Pb solders,[9] and fluxes of all types can also be used, with the choice of specific flux depending on the base metal(s) being joined.

In describing these solders, it is customary to give the Sn content first, so a "60–40 solder" is a 60 wt.% Sn/40 wt.% Pb alloy. Sn–Pb solders, like some other solders, are referred to as "soft solders" or "soft solder alloys" because they are, in fact, physically soft and low melting. Table 8.6 lists several commonly used soft solder alloys of various compositions and their uses.

The metallurgy of the Sn–Pb alloy system is fairly representative of all solder alloys and is similar to the metallurgy of brazing alloys (see Subsection 7.5.3) in that it is the metallurgy of a eutectic system. Figure 8.7 shows the constitutional or equilibrium phase diagram for the Sn–Pb alloy system. It should be immediately apparent that this is a typical diagram for a eutectic alloy system, in this case with a solid solution at the Pb-rich end and a much more limited solubility solid solution at the Sn-rich end. The highest temperature at which a metal or alloy is completely solid (i.e., the "solidus temperature") is given by curve ACEDB, called the "solidus curve." The lowest temperature at which a metal or alloy is completely liquid (i.e., the "liquidus temperature") is given by curve AEB, called the "liquidus curve." At the extreme ends of the diagram are the pure metals, Pb on the left and Sn on the right. As is always the case for pure metals, pure Pb and pure Sn each melt at a specific, discrete temperature, called the "melting point." Pure Pb melts at 327°C (621°F), shown by point A, while pure Sn melts at 232°C (450°F), shown by point B. Between these two pure metals are solid solution-strengthened alloys that melt over a range of temperatures, beginning at the solidus and ending at the liquidus. The temperature differential between the solidus (ACEDB) and the liquidus (AEB) is called the "melting" or "freezing" range, and within this range the alloy is partially melted or, alternatively, partially solidified. The only exception is at point E, where there is a composition that melts at a single, discrete temperature, like a pure crystalline material. This, however, is not a pure material; it is a microstructural constituent consisting of intimately mixed Pb-rich and Sn-rich solid solutions. The two phases are usually distinguishable from one another, and often (but not always!) are arranged in layers or laminations to produce what is called a "lamellar structure," such as that shown in Figure 8.8. This constituent is called a "eutectic" and is the alloy with the lowest liquidus temperature in the entire

[9] In fact, most soldering processes, cleaning processes, and fluxes, as well as electronic packaging and printed wire board materials, were developed knowing that Sn–Pb solders, particularly the 63Sn-37Pb eutectic, would be used. Hence, operating temperatures for processes and survivability temperatures for materials, were selected and/or adjusted for the eutectic temperature of 183°C (361°F). This makes finding a Pb-free replacement for these solders extra difficult because any such replacement should, ideally, have a use temperature no higher than the Sn–Pb eutectic. Many processes and materials become useless for soldering if they cannot meet this requirement.

Table 8.6 Common Soft-Solder Alloys and Their Uses

Properties				*Comparable National Material Standards and Designations*				
Uses	*Designation*	*Melting Point or Range, °C*	*Density at 20°C, g/cm³*	*France*	*Germany*	*Great Britain*	*Japan*	*USA*
Solder manufacture, tinning	Sn99.95	232	7.3		Sn99.95 DIN 1704	grade T_1 BS 3252	Tin metal class 1a JIS H 2108	Grade AA ASTM B 339-72
Joining electronic components	SnPb40	183–189	8.5	60/40 NF C90-550	L-Sn60Pb DIN 1707	BS solder K and KP BS 219	H60S H60A JIS Z3282	Alloy Grades 60A and 60B ANSI/ASTM B 32-76 SN 60 QQ-S-571
Step soldering, tinning of winding wire	PbSn35	183–245	9.5		L-PbSn35(Sb) DIN 1707	BS solder H BS 219	H35S H35A JIS Z 3282	Alloy Grade 35A and 35B ANSI/ASTM B 32-76 Pb65 QQ-S-71
Soldering of mechanical components	PbSn20Sb1	183–277	9.8				H20B JIS Z 3282	Alloy Grade 20C ANSI/ASTM B 32–76 Sn20 QQ-S-571
High service temperature	PbSn5	300–315	11.2	5/95 NF C90-550			H5S H5A JIS Z 3282	Alloy Grade 5A and 5B ANSI/ASTM B 32-76 Sn 5 QQ-S-571
Good strength at elevated temperatures	PbAg2.5Sn1	295–320	11.3	0/97/Ag3 NF C90-550	L-PbAg3 DIN 1707			Alloy Grade 1,5S ANSI/ASTM B 32-76 Ag 1,5 QQ-S-571
Solder manufacture	Pb99.99	327	11.3		Pb99.99 DIN 1719	Pb99.99 BS 334 Type A	Pig lead special class JIS H 2105	Corroding lead ASTM B 29-55

Note: It is the custom, in the abbreviated designation of the composition of the solder, to mention the metal with the highest content first.
Example: Solder SnPb40, PbSn50, PbSn40; mass percent of tin 60, 50, 40 respectively.
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Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 326, Table 9.4, 1993, with permission of Elsevier Science, Burlington, MA.

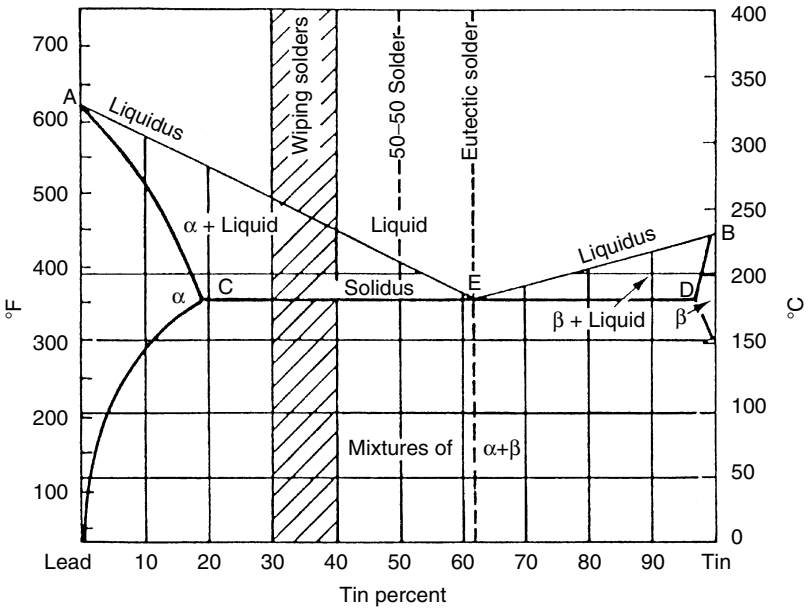

Figure 8.7 Phase diagram for the Sn–Pb binary alloy system. (Reprinted from *Soldering Manual*, 2nd edition, Fig. 2.1, page 5, American Welding Society, Miami, FL, 1978, with permission.)

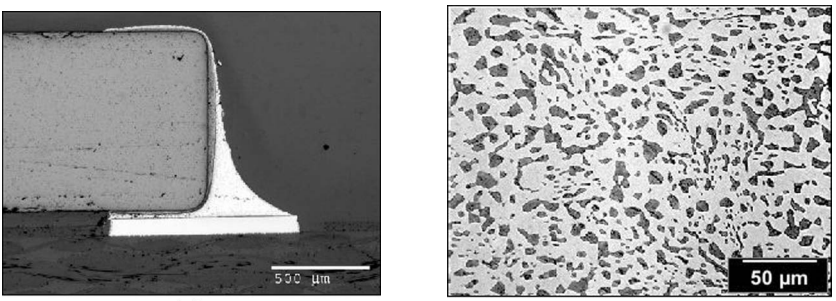

Figure 8.8 A photomacrograph (a) and photomicrograph (b) of a typical near-eutectic 60Sn–40Pb solder showing the self-formation of smooth fillets due to wetting action (a) and the eutectic constituent made up of lamella of the Sn-rich and Pb-rich solid solution phases (b) (Courtesy of Sandia National Laboratories, Albuquerque, NM, with permission.)

alloy system.[10] The eutectic composition is approximately 63 wt.% Sn/37 wt.% Pb (point E), and the eutectic temperature is 183°C (361°F).

[10] To be precisely correct, a eutectic is a reaction in which, on cooling, a liquid forms two solid phases (in a binary system) at the eutectic temperature. Such reactions are located between two solid phases, and, between those two phases, the eutectic temperature is the lowest temperature at which liquid forms on heating. In more complex alloy systems, with many intermediate solid phases, there can be more than one eutectic reaction and thus more than one eutectic temperature, depending on the composition.

Solders containing 19.5 wt.% (point C) to 97.5 wt.% (point D) Sn all have the same solidus temperature (i.e., they all start melting at the same temperature, namely 183°C (361°F)). Only the eutectic composition, however, becomes completely liquid at 183°C (361°F). All other compositions in this range are only partially melted at 183°C (361°F), and so are less fluid than the eutectic at this temperature.

There are many more important solder compositions in the Sn-Pb system, as shown in Table 8.7, which lists Sn–Pb solders from ASTM Specification B32. Some characteristics of some of the more specific alloys of importance follow:

- 5–95 is relatively high melting, has a narrow melting and freezing range, and is poor in terms of wetting and flow compared to higher Sn alloys. Mechanical properties of this high-Pb alloy are better at 149°C (300°F) than most other alloys with more Sn.
- The 10–90, 15–85, and 20–80 solders have progressively lower liquidus and solidus temperatures, a wider melting range, and better flow than 5–95. All are prone to solidification cracking or "hot tearing," however, if movement occurs during cooling (e.g., from thermal contraction stresses).
- The 25–75 and 30–70 solders have lower liquidus temperatures than all previous, more Pb-rich solders, but the same as 20–80. The melting range is thus narrower, so there is a lesser tendency toward hot tearing.
- The 35–65, 40–60, and 50–50 solders have low liquidus temperatures and, as a group, have the best combination of wetting, strength, and economy.
- The 60–40 solder is used whenever exposure temperature restrictions are critical for the assembly or some of its components, since the composition is close to the eutectic. It is cheaper because it contains slightly less expensive Sn than the true eutectic at 63–37.
- The 70–30 alloy is a special-purpose solder used where a high Sn content is required for wetting or other compatibility.

Besides these alloys, pure Pb and pure Sn can be and are used for soldering.

8.5.3 Tin–Antimony and Tin–Lead–Antimony Solders

Tin–antimony (Sn–Sb) solders are generally stronger than the Sn–Pb solders, since Sb is an effective solid solution strengthener in Sn. This is especially true at somewhat higher temperatures than can be tolerated by Sn–Pb alloys, resulting in good creep strength where that property is required. The Sn–Sb phase diagram is shown in Figure 8.9a. The 95 wt.% Sn/5 wt.% Sb solder provides a narrow melting and solidification range at temperatures higher than the Sn–Pb eutectic. For this reason, this alloy is a good choice for mechanical applications such as plumbing, refrigeration and air conditioning. One serious problem is that Sb, like Pb, is toxic, so the alloy should be handled with care (especially its vapors!) and use in certain applications, such as plumbing for potable water or for food or beverage processing or handling equipment, should be avoided.

Antimony may be added to Sn–Pb solders as a substitute for some of the Sn. Additions of up to 6 wt.% increase the mechanical properties with only slight impairment of soldering characteristics (e.g., wetting and flow).

Table 8.7 List of Important Tin–Lead (Sn–Pb) Solders from ASTM Specification B32

ASTM Alloy Grade	*Fed. Spec. QQ-S-71*	*Tin % Desired*	*Lead % Nominal*	*Antimony %*			*Silver % Desired*	*Melting Range*			
								Solidus		*Liquidus*	
				Minimum	*Desired*	*Maximum*		*°C*	*°F*	*°C*	*°F*
70A		70	30	-	-	0.12	-	183	361	192	378
70B	Sn	70	30	0.20	-	0.50	-				
63A		63	37	-	-	0.12	-	183	361	183	361
63B	Sn63	63	37	0.20	-	0.50	-				
	Sn62	62	36	0.20	-	0.50	2				
60A		60	40	-	-	0.12	-	183	361	190	374
60B	Sn60	60	40	0.20	-	0.50	-				
50A		50	50	-	-	0.12	-	183	361	216	421
50B	Sn50	50	50	0.20	-	0.50	-				
45A		45	55	-	-	0.12	-	183	361	227	441
45B		45	55	0.20	-	0.50	-				
40A		40	60	-	-	0.12	-	183	361	238	460
40B	Sn40	40	60	0.20	-	0.50	-				
40C		40	58	1.8	2.0	2.4	-	185	365	231	448
35A		35	65	-	-	0.25	-	183	361	247	477
35B	Pb35	35	65	0.20	-	0.50	-				
35C	Sn35	35	63	1.6	1.8	2.0	-	183	365	243	470
30A		30	70	-	-	0.25	-	183	361	255	491
30B	Pb30	30	70	0.20	-	0.50	-				
30C	Sn30	30	68.4	1.4	1.6	1.8	-	185	364	250	482
25A		25	75	-	-	0.25	-	183	361	266	511
25B		25	75	0.20	-	0.50	-				

25C		25	73.7	1.1	1.3	1.5	-	184	364	263	504
20B	Pb20	20	80	0.20	-	0.50	-	183	361	277	531
20C	Sn20	20	79	0.80	1.0	1.20	-	184	363	270	517
15B		15	85	0.20	-	0.50	-	227	440	288	550
10B	Sn10	10	90	0.20	-	0.50	-	268	514	299	570
5A		5	95		-	0.12	-	270	518	312	594
5B	Sn5	5	95	0.20	-	0.50	-				
2A		2	98	-	-	0.12	-				

Note: Bismuth content allowed for the above alloys is 0.25% maximum. The allowable copper content is 0.08% maximum, the iron content is 0.02% maximum, the aluminum content is 0.005% maximum, and the zinc content is 0.005%. The arsenic content of solders containing 60 to 70% tin is 0.03%, for 45 to 50% tin the arsenic allowed is 0.025%, and for all solders from 20 to 40% tin the arsenic limit is 0.02%.

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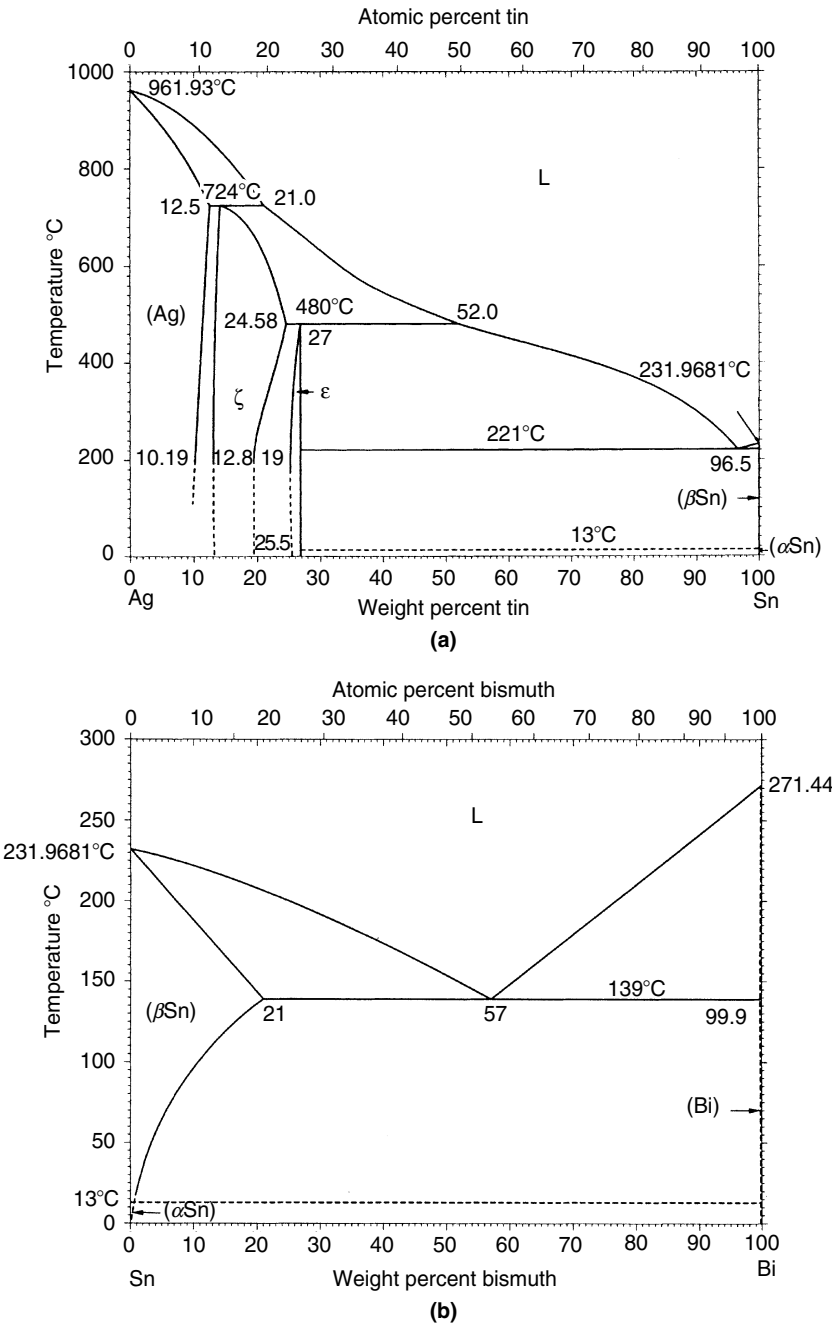
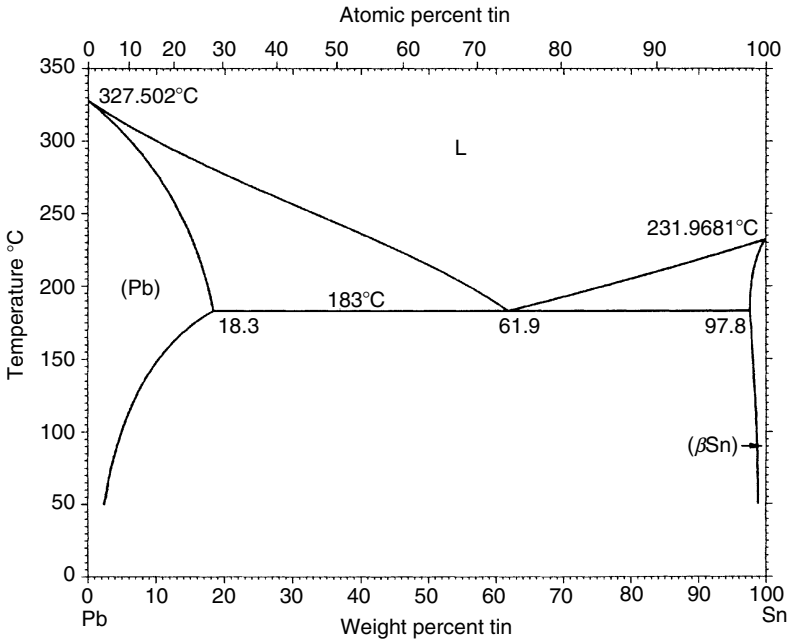


Figure 8.9 Some important phase diagrams for various binary alloy systems relevant to soft solders, including (a) Sn–Ag, (b) Sn–Bi,



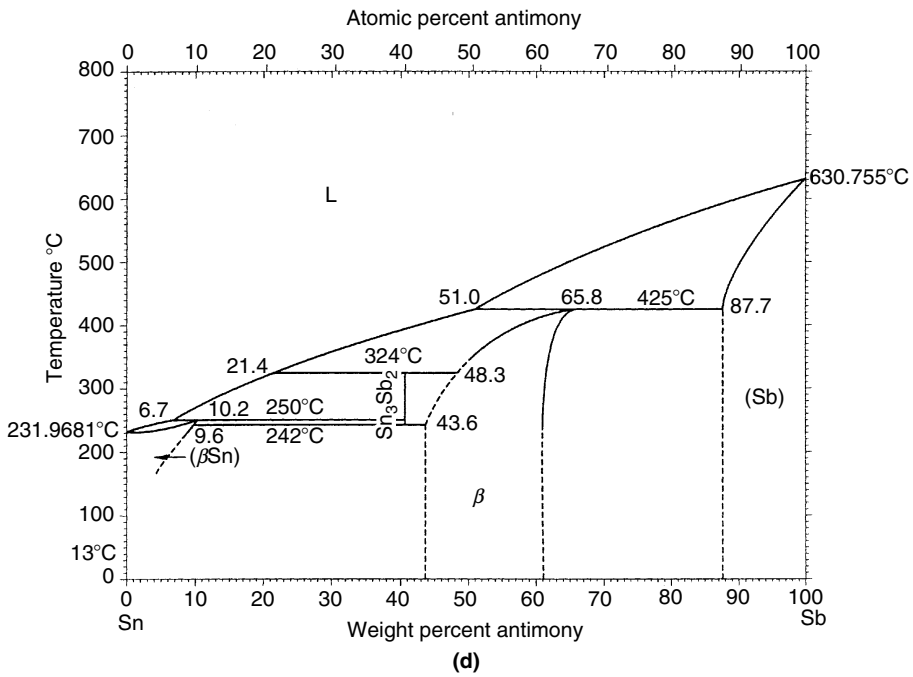


Figure 8.9 (*cont'd*) (c) Sn–Pb (shown as Pb–Sn), (d) Sn–Sb, and

(*Continues*)

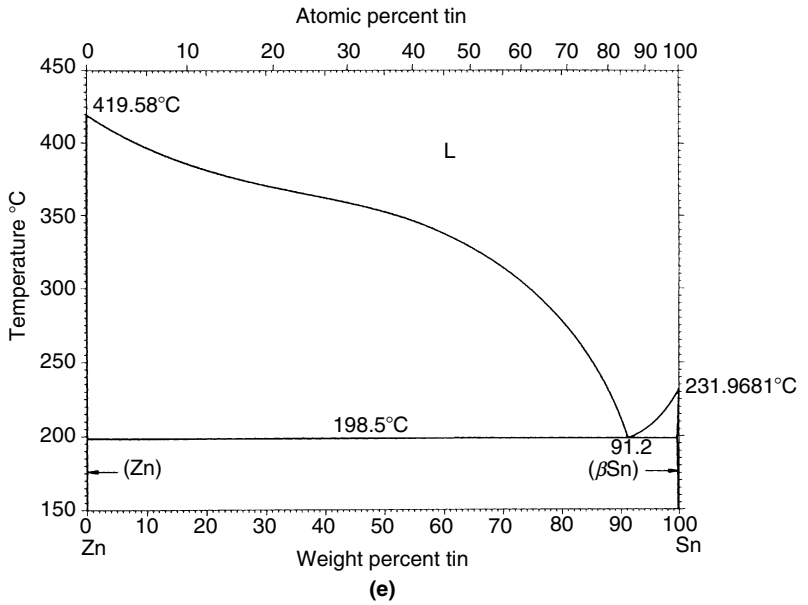


Figure 8.9 (*cont'd*) (e) Sn–Zn (shown as Zn–Sn). (Reprinted from *Binary Alloy Phase Diagrams*, Vols. 1 and 2, T.B. Massalski, Editor, American Society of Metals, Metals Park, OH, 1986, with permission.)

8.5.4 Tin–Silver and Tin–Lead–Silver Solders

The Sn–Ag, Pb-free solders are most often used for soldering of stainless steel for food-processing applications, where Pb must be avoided because of its toxicity. Interest in Sn–Ag alloys as solders is growing as a Pb-free alternative even for manufacturing electronic and micro-electronic items. The Sn–Ag binary phase diagram is shown in Figure 8.9b.

The high Pb Sn–Pb solders with Ag added provide higher soldering temperature, exhibit good tensile, shear, and creep strength, and are excellent for cryogenic applications due to their toughness. The 62 wt.% Sn/36 wt.% Pb/2wt.% Ag ternary alloy is used to solder to Ag-coated surfaces for electrical applications. The addition of Ag retards Ag dissolution "leaching" of the coating, as well as increases creep strength. On the other hand, even a trace of Pb contamination in the Sn–Ag eutectic lowers its melting point dramatically from 221°C (429°F). Hence, Pb is often said to "poison" Sn–Ag solders.

8.5.5 Tin–Zinc Solders

A large number of Sn–Zn solders are used for joining aluminum and its alloys. Galvanic corrosion is minimized by their use. The Sn–Zn binary phase diagram is shown in Figure 8.9c.

Table 8.8 lists various Sn-bearing binary and ternary solders with Sb, Sb+Pb, Ag, Ag+Pb, and Zn, along with their solidus and liquidus temperatures and melting ranges.

Table 8.8 List of Various Sn-Bearing Binary and Ternary Solders

ASTM Class.	Composition, wt.%					Solidus		Liquidus		Melting Range	
	Sn	Pb	Sb	Ag	Zn	°C	°F	°C	°F	°C	°F
5	5	95	–	–	–	300	572	314	596	14	24
10	10	90	–	–	–	268	514	301	596	14	24
15	15	85	–	–	–	225	437	290	553	65	116
20	20	80	–	–	–	183	361	280	535	97	174
25	25	75	–	–	–	183	361	267	511	84	150
30	30	70	–	–	–	183	361	255	491	72	130
35	35	65	–	–	–	183	361	247	477	64	116
40	40	60	–	–	–	183	361	235	455	52	94
45	45	55	–	–	–	183	361	228	441	45	80
50	50	50	–	–	–	183	361	217	421	34	60
60	60	40	–	–	–	183	361	190	374	7	13
70	70	30	–	–	–	183	361	192	378	9	17
95TA	95	–	5	–	–	232	450	240	464	8	14
	96	–	–	4	–	221	430	221	430	0	0
	62	36	–	2	–	180	354	190	372	10	18
	5	94.5	–	0.5	–	294	561	301	574	7	13
	2.5	97	–	0.5	–	303	577	310	590	7	13
	1	97.5	–	1.5	–	309	588	309	588	0	0
	91	–	–	–	9	199	390	199	390	0	0
	80	–	–	–	20	199	390	269	518	70	128
	70	–	–	–	30	199	390	311	592	112	202
	60	–	–	–	40	199	390	340	645	141	255
	30	–	–	–	70	199	390	375	708	176	318
96.5TS	96.5	–	–	3.5	–	221	430	221	430	0	0

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8.5.6 Cadmium–Silver Solders

Cadmium–silver (Cd–Ag) solders, whose phase diagram is shown in Figure 8.10a, are used where service temperatures will be higher than permissible with lower melting solders. Joint strengths can be very high (i.e., upwards of 172.4 MPa (25,000 psi)) when used to join copper. Cadmium, like Pd and Sb, is toxic, however, so care must be exercised during both soldering and subsequent use and disposal.[11]

[11] The problem with toxic low-melting metals (e.g., Pb, Sb, and Cd, as well as Hg and Ga) and their alloys is that being low melting, they also have high vapor pressures. High vapor pressures, in turn, lead to the production of metal-vapor fumes that enter the lungs to lead to toxic events.

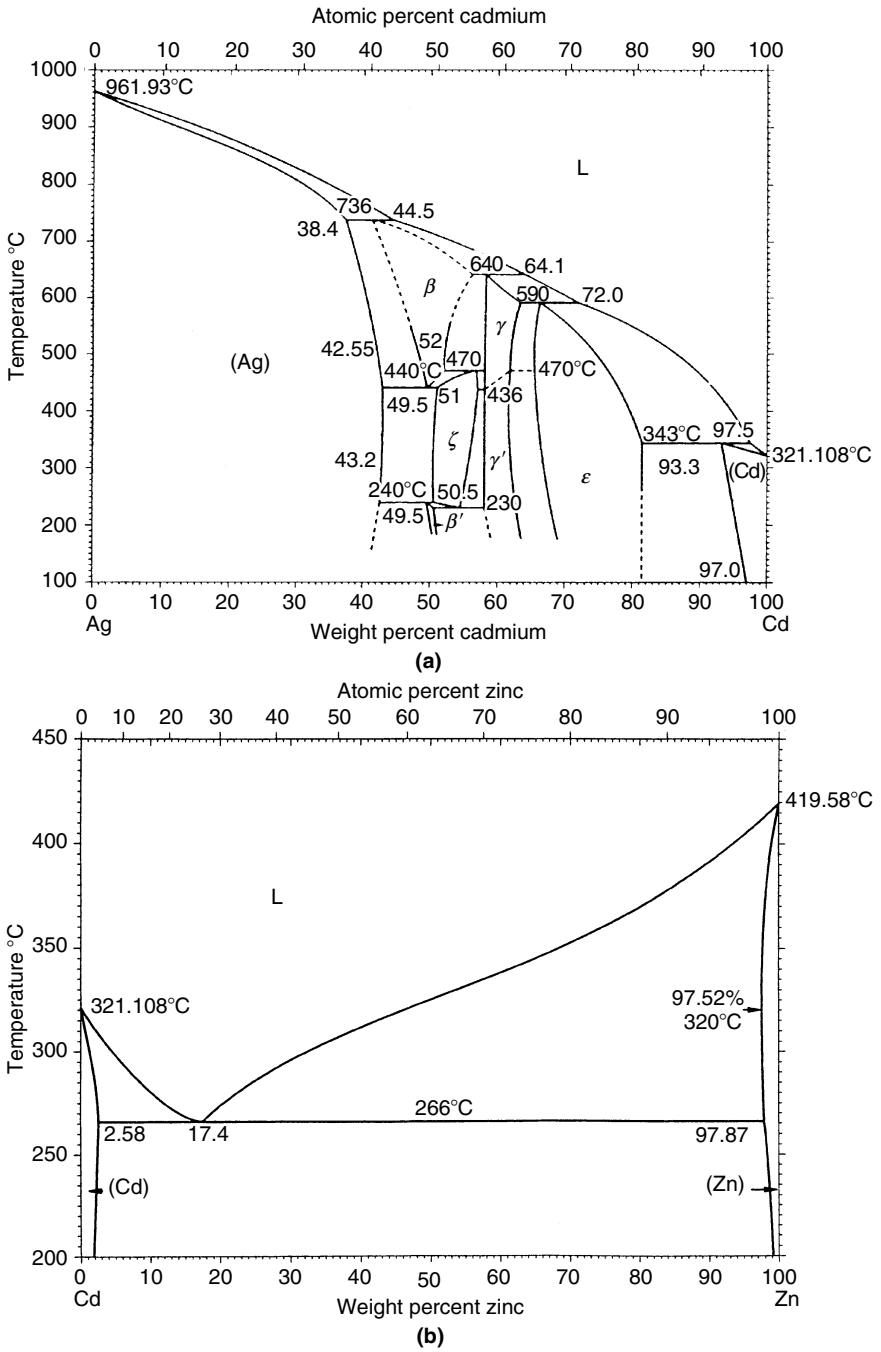

Figure 8.10 Some other important solder alloy phase diagrams, including: (a) Cd–Ag (shown as Ag–Cd), (b) Cd–Zn,

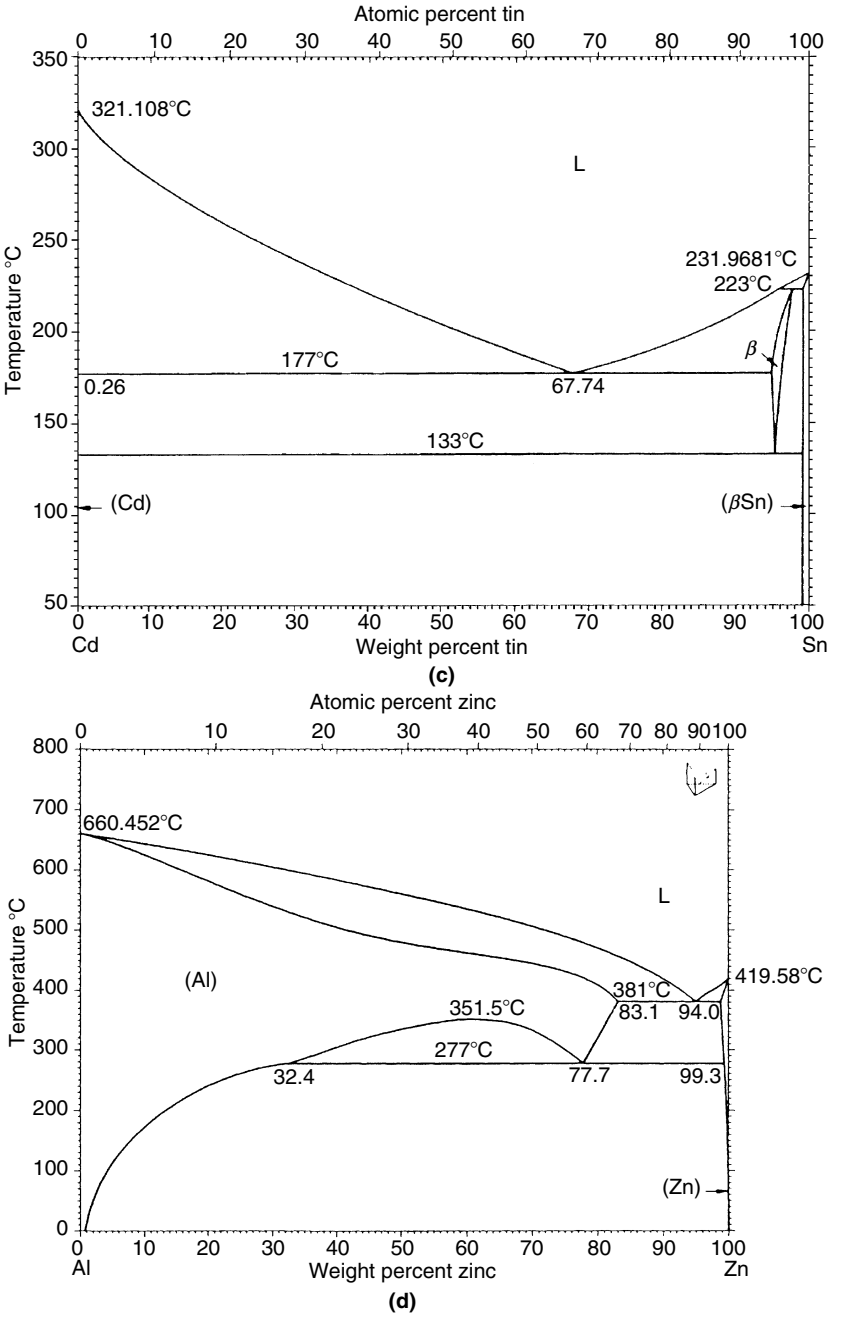

Figure 8.10 (*cont'd*) (c) Cd–Sn, and (d) Zn–Al (shown as Al–Zn). (Reprinted from *Binary Alloy Phase Diagrams*, Vols. 1 and 2, T.B. Massalski, Editor, American Society of Metals, Metals Park, OH, 1986, with permission.)

Table 8.9 Some Important Cd–Ag, Cd–Zn, and Zn–Al Solders

Composition, Wt. %				*Solidus*		*Liquidus*		*Melting Range*	
Cd	*Ag*	*Zn*	*Al*	*°C*	*°F*	*°C*	*°F*	*°C*	*°F*
95	5	–	–	338	640	343	740	55	100
82.5	–	17.5	–	265	509	265	509	0	
40	–	60	–	265	509	335	635	70	126
10	–	90	–	265	509	399	750	134	241
–	–	95	5	382	720	382	720	0	0

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8.5.7 Cadmium–Zinc Solders

Cadmium–zinc (Cd–Zn) solders are used for soldering aluminum and its alloys. Strengths and corrosion resistance are intermediate, but cost is lower than Cd–Ag solders. The toxicity of Cd fumes again must be considered carefully in processing. The Cd–Zn phase diagram is shown in Figure 8.10b.

8.5.8 Zinc–Aluminum Solders

Zinc–aluminum (Zn–Al) solders, the phase diagram for which is shown in Figure 8.10d, are specially designed for soldering aluminum alloys. Resulting joints have high strength and good corrosion resistance, much like Al–Zn alloys. Some important solder compositions and melting temperatures and ranges for Cd–Ag, Cd–Zn, and Zn–Al solders are given in Table 8.9.

8.5.9 Fusible Alloys

Bismuth-containing solders, or so-called "fusible alloys," are useful for soldering operations where the soldering temperature must be kept below 183°C (361°F), which is the lowest melting or eutectic temperature for Sn–Pb soft solders. Such solders are required for (1) soldering of heat-treated surfaces where higher soldering temperatures would cause softening; (2) soldering joints where adjacent materials must be kept from overheating (e.g., because of their inherent heat sensitivity or combustibility); (3) "step-soldering" (analogous to "step-brazing," Subsection 7.4.8) to prevent remelting of a nearby solder joint made at a higher temperature; and (4) soldering of temperature-sensing devices, where the device is activated when the fusible alloy melts at a relatively low temperature (e.g., fire sprinkler heads). Fusible solders are sometimes used for mounting or fixturing parts during machining or for producing removal mandrels for use in spin forming of sheet metal or filament winding of composites. In the latter case, the mandrel is removed by melting in cases where it is trapped by the formed part's re-entrant shape.

Table 8.10 List of Low-Melting or Fusible Alloys Used as Solders

Melting Point °C	*Composition in Mass Percent*					*Other Elements*	*Generic Name*
	Sn	*Pb*	*Bi*	*In*	*Cd*		
16				24		76 Ga	
20	8					92 Ga	
25						95 Ga; 5 Zn	
29.8						100 Ga	
46.5	10.8	22.4	40.6	18	8.2		
47.2	8.3	22.6	44.7	19.1	5.3		
58	12	18	49	21			
61	16		33	51			
70	13.1	27.3	49.5		10.1		Lipowitz's alloy
70–74	12.5	25	50		12.5		Wood's metal
72.4		34	66				
79	17		57	26			
91.5		40.2	51.7		8.1		
93	42		44	14			
95	18.7	31.3	50				Newton's metal
96–98	25	25	50				d'Arcet's metal
103.0	26		53.5		20.5		
96–110	22	28	50				Rose's metal
117	48		52				
125		43.5	56.5				
127.7			75	25			
139	43		57				
144		62	38				
145	49.8	32		18.2			
156.4			100				
170	57					43 Tl	
176	67			33			
178	62.5	36				1.5 Ag	
180	63	34	3				
183	61.9	38.1					

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The compositions and melting properties of a selection of low-melting, fusible alloys are given in Table 8.10.

8.5.10 Indium Solders

Indium (In) solders offer special properties, namely, very low vapor pressures for use in high vacuum seals or outer space, and the ability to wet and adhere to a wide variety of

metals as well as a wide variety of ceramics and glasses. Some nonmetallic materials that have been successfully soldered with In-based solders include glass, quartz, marble, granite, mica, porcelain, cement and concrete, brick, aluminum oxide, copper oxide, germanium oxide, iron oxide, magnesium oxide, nickel oxide, titanium oxide, and zirconium oxide. The 50 wt.% In/50 wt.% Sn alloy, shown in Table 8.11, adheres to glass readily and can be used for glass-to-glass or metal-to-glass joining by soldering (see Chapter 12, Subsection 12.8.4). Phase diagrams for In–Pb and In–Sn are shown in Figure 8.11.

Table 8.11 Some Important In-Based Solders

Composition, Wt. %					*Solidus*		*Liquidus*		*Melting Range*	
In	*Sn*	*Bi*	*Pb*	*Cd*	*°C*	*°F*	*°C*	*°F*	*°C*	*°F*
50	50	–	–	–	117	243	125	257	8	14
25	37.5	–	37.5	–	138	280	138	280	0	0
50	–	–	50	–	180	356	209	408	29	52
19.1	8.3	44.7	22.6	5.3	47	117	47	117	0	0
21	12	49	18	–	58	136	58	136	0	0
4.0	12.8	48.0	25.6	9.6	61	142	65	149	4	7
52	48	–	–	–	117	243	117	243	0	0

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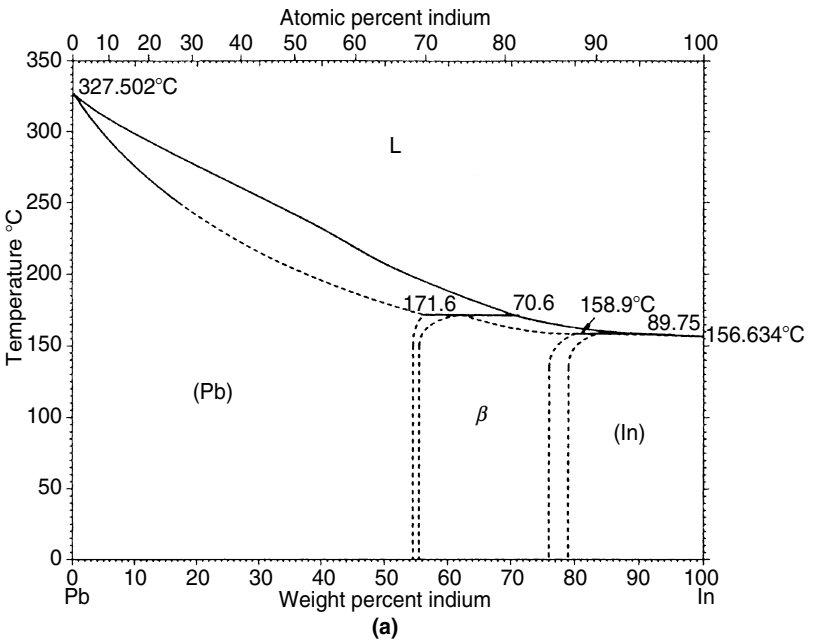
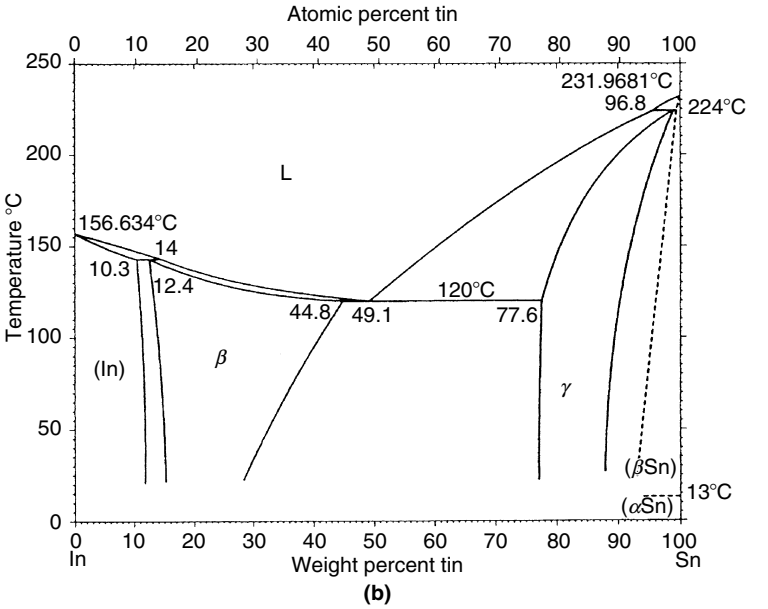


Figure 8.11 Phase diagrams for some important In-based solders, including (a) In–Bi (shown as Bi–In),



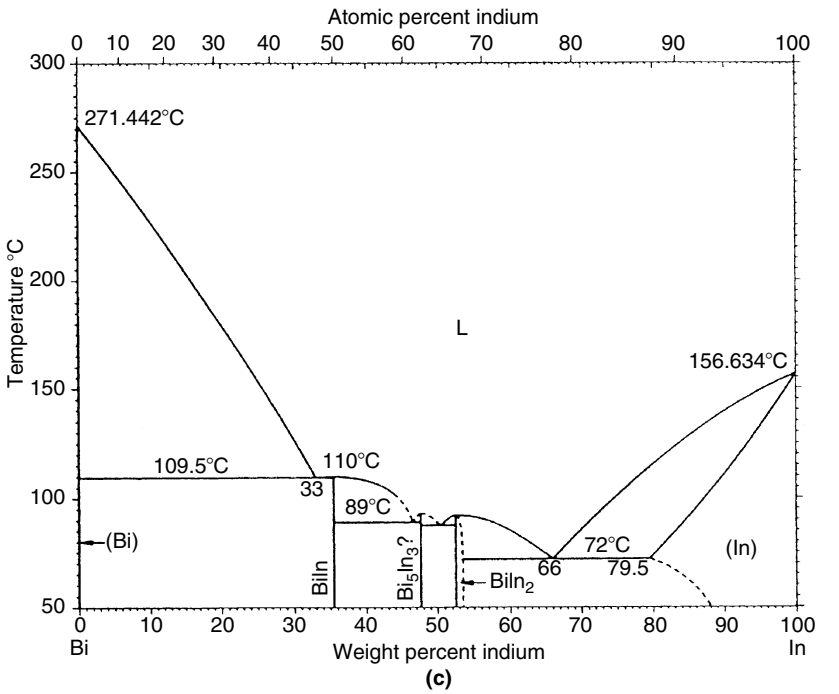


Figure 8.11 (*cont'd*) (b) In–Pb (shown as Pb–In), and (c) In–Sn. (Reprinted from *Binary Alloy Phase Diagrams*, Vols. 1 and 2, T.B. Massalski, Editor, American Society of Metals, Metals Park, OH, 1986, with permission.)

Table 8.12 Some Important Special Solder Alloys

Composition, Wt. %					*Solidus*		*Liquidus*		*Melting Range*	
Au	*Sn*	*Ge*	*Si*	*In*	°*C*	°*F*	°*C*	°*F*	°*C*	°*F*
80	20	–	–	–	280	536	280	536	0	0
88	–	12	–	–	356	673	356	673	0	0
96.4	–	–	3.6	–	370	698	370	698	0	0
82	–	–	–	18	451	843	485	905	34	62
Sn	*Ag*	*Sb*	*Ge*	*Al*	*Solidus*		*Liquidus*		*Range*	
65	25	10	–	–	233	451	?	??	?	?
–	–	–	55	45	242	795	424	795	0	0

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8.5.11 Other Special Solders

Besides these more common solders, there are many special solders for particular applications. The compositions of some of these special solders and their melting properties are listed in Table 8.12.

One particularly important special solder is the Au–Si eutectic used for die attachment[12] in hermetic electronic packages, particularly for military applications. The process is often called "eutectic bonding" or "die bonding." Both Au and Si melt at temperatures above 1,000°C (1,800°F), but their phase diagram exhibits a eutectic composition containing 3 wt.% Si, which melts at 363°C (685°F). In the ideal case, a Si die is placed into an Au-plated ceramic package's cavity. The package is then heated to a temperature above that of the Au–Si eutectic, usually above 425°C (795°F). The Si diffuses into the Au until the eutectic composition is approached and melting begins. The liquid front advances in the Au as Si continues to diffuse, and an intimate bond is formed. The process is arrested—or "self-limited"—by adjusting the relative proportions of Au and Si.

Several other Au-based solders are shown in Table 8.12, including binaries with Sn, Ge, and In. While obviously expensive, these alloys offer extraordinary corrosion resistance, good wettability, and compatibility with Si that justify their use in semiconductor device assembly and package sealing.

Two other specialty solders are 65 wt.% Sn/25 wt.% Ag/10 wt.% Sb and 55 wt.% Ge/45 wt.% Al. These alloys were each developed for electronic applications; the first was developed for applications requiring very high strength, the second for applications requiring very high service temperature. The Sn–Ag–Sb alloy has a tensile strength of 125 MPa (18 ksi), while the Ge–Al alloy has a eutectic melting temperature of 424°C (795°F). Phase diagrams for some of these special solders are shown in Figure 8.12.

[12] A *die*, in this context, is the individual semiconductor element or integrated circuit after it has been cut or separated out of the processed semiconductor wafer. This is distinct from a completely packaged or encapsulated integrated circuit with leads attached.

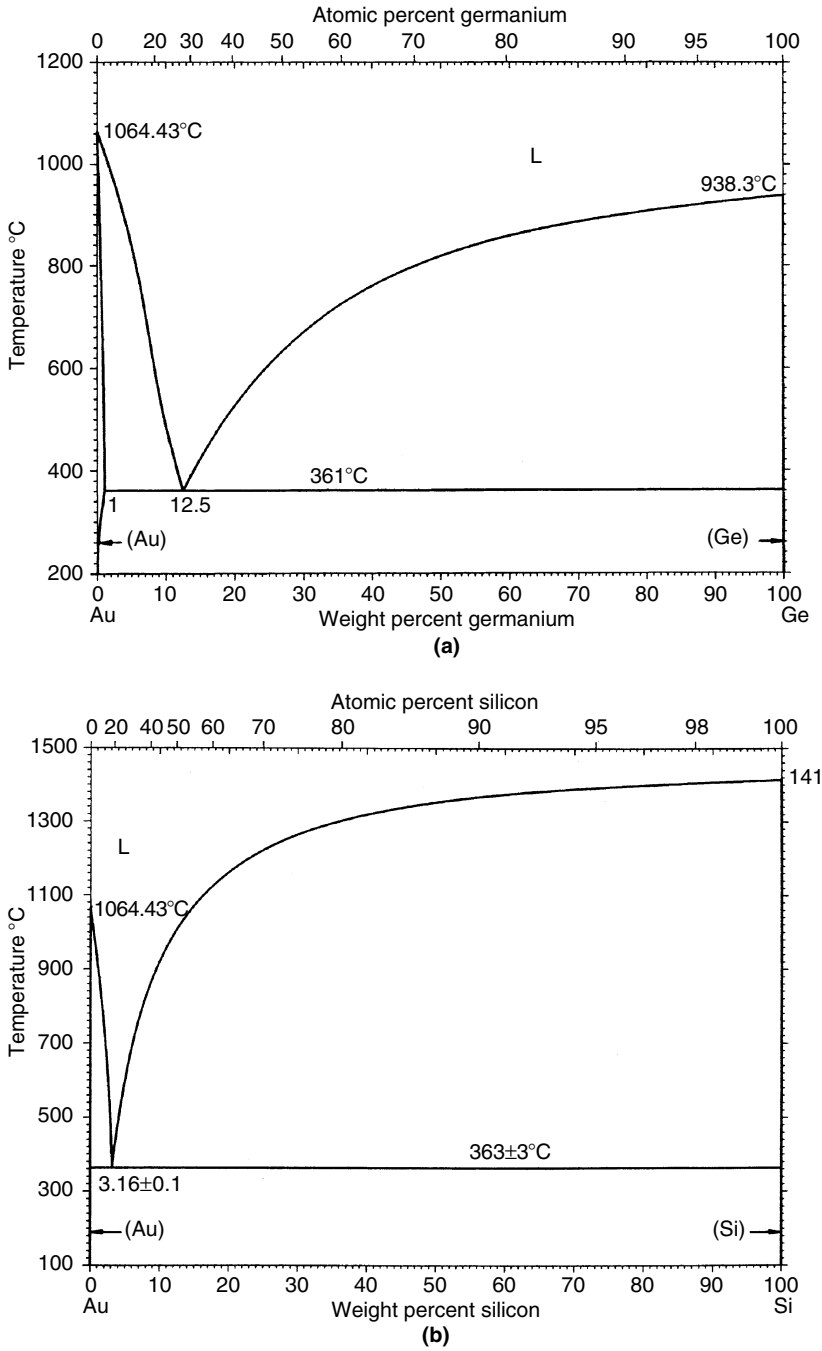


Figure 8.12 Phase diagrams for some special solders, including: (a) Au–Ge and (b) Au–Si (*Continues*)

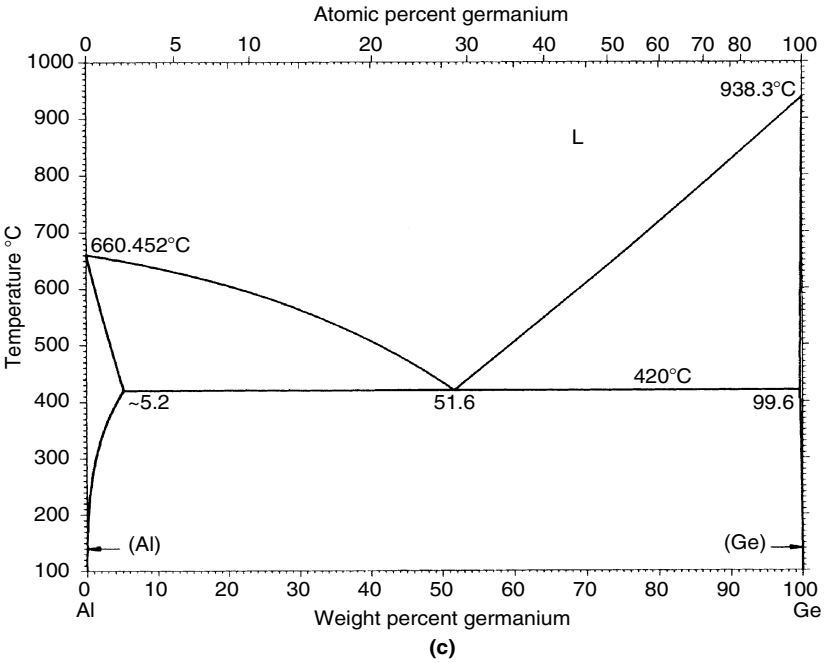


Figure 8.12 (*cont'd*) and (c) Al–Ge. Interestingly, the Al–Si phase diagram is important for Al–Si brazing fillers, classified as BAlSi types. (Reprinted from *Binary Alloy Phase Diagrams*, Vols. 1 and 2, T.B. Massalski, Editor, American Society of Metals, Metals Park, OH, 1986, with permission.)

Two other recent developments in solders have emerged—at least in research laboratories. This first development involves the use of a dispersed, thermally stable second phase in otherwise traditional solders, especially the Sn–Ag–Cu ternary eutectic. The idea of the dispersed phase is to offer improved creep strength, which in solder joints tends to relate very closely to their resistance to thermomechanically induced fatigue (which turns out to be the predominant cause of failure of solder joints in service). Another development is the use of encapsulated Ti to make otherwise traditional solders (such as Sn–Pb and Sn–Ag, without or with ternary additions of Cu). By encapsulating small Ti particles in a thin rare earth metal shell and then mechanically working the solder (as a paste) between joint elements to be soldered, the shells are broken, exposing the Ti to react with an otherwise stable substrate. These seem to offer potential for soldering ceramics and carbonaceous base materials, whether monolithic or reinforced composites.

8.5.12 Physical Forms of Solders

Solders, like braze fillers, come in many physical forms to satisfy many different applications. Forms include pigs (which are large tub-shaped ingots), ingots, bars,

Table 8.13 Commercially Available Solder Product Forms

Pig	Available in 25 and 45 kg (50 and 100 lb) pigs
Ingots	Rectangular or round; 1–4, 2–3, and 4–3 kg (3, 5, and 10 lb)
Bars	Available in many cross-sections, weights, and lengths
Paste or cream	Available as mixture of powdered solder and flux
Foil sheet or ribbon	Available in various thicknesses and widths
Segment or drop	Triangular bar or wire cut into any number of desired pieces or lengths
Wire, solid	Diameters of 0.25 to 6.36 mm (0.010 to 0.250 in.); spools
Wire, flux-cored	Solder covered with rosin, organic, or inorganic fluxes; diameters as above
Preforms	Unlimited range of sizes and shapes to meet need

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 341, Table 9.11, 1993, with permission of Elsevier Science, Burlington, MA.

solid wires, flux-cored wires, foils, sheets or ribbons, preforms of all shapes and sizes, segments or drops, and pastes or creams (which are just smoother pastes containing finer particles of solder). These types are listed in Table 8.13.

In addition to the common commercially available forms, some special forms have come into use in modern electronic assembly for establishing interconnection between devices and the integrating substrate. Two examples are "solder bumps" and "tape automated bonding" (TAB). *Solder bumps* are round solder balls that are bonded to a transistor contact area and used to make connections to a conductor by face-down or "flip-flop" bonding techniques. One solder bump method is IBM's C4, which stands for "controlled collapse chip connection." The idea of bumps in general, and C4 in particular, is precise control of the amount (i.e., volume) of solder available at each intended joint. The driving force for this is the experiential knowledge that controlled and consistent solder bead or joint shape leads to improved life under thermomechanical fatigue. *Tape automated bonding,* or TAB, is a highly automated method for surface mounting electronic packages that can provide interconnection of chips with large numbers (up to 500) of input/output (I/O) terminals. In TAB, a continuous polymer tape is fabricated with fine-pitched metal lead frames spaced along its length. A window is made in the center of each frame where the chip is to be placed. The leads of the lead frame are then bonded to the chips, on which bonding platforms ("bumps") have been deposited. Bumps serve as bonding platforms for subsequent joining, usually by soldering but possibly by other means, such as adhesive bonding.

8.6 FLUXES AND ATMOSPHERES FOR SOLDERING

8.6.1 The Need for Fluxes or Atmospheres in Soldering

A soldering flux is a liquid, solid (powder), or gaseous material that, when heated, is capable of promoting or accelerating the wetting of metals by molten solders. The purpose of the flux is to remove small amounts of oxide and other tarnish compounds from the surfaces being soldered by the process of chemical reduction, and to keep

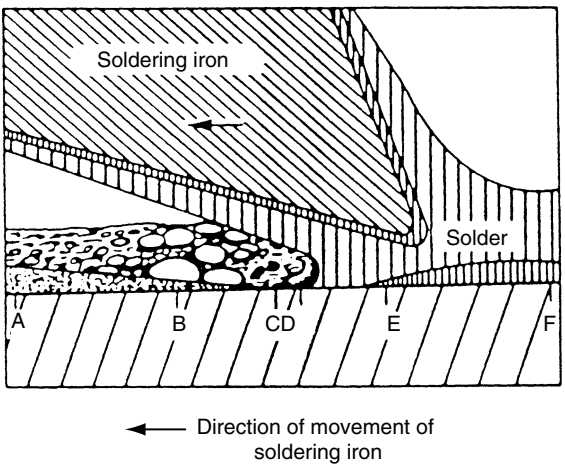


Figure 8.13 Schematic illustration of the mechanism by which fluxes clean a substrate surface during soldering. (Reprinted from *Soldering Manual*, 2nd edition, Fig. 3.1, page 14, American Welding Society, Miami, FL, 1978, with permission.)

those oxides or tarnish compounds from reforming by remaining on the surfaces until displaced by the molten solder. A fluxing compound or flux should become most chemically active just below the melting point (i.e., the solidus) of the solder and remain active to at least the liquidus temperature of the solder. During soldering, the flux should be displaced by the molten solder. This requires the solder to be denser than the molten flux and reduce the surface free energy of the solder–substrate interface over that of the flux–substrate interface. The mechanism by which fluxes clean oxidized base metal surfaces to promote wetting by molten solder is shown in Figure 8.13.

Fluxes may be classified into three groups: (1) naturally occurring rosin fluxes, which are the least aggressive and only mildly corrosive to base metals or solders; (2) organic fluxes, which are moderately aggressive and mildly corrosive to base metals and solders; and (3) inorganic fluxes, which are the most aggressive and corrosive to many base metals and some solders.

8.6.2 Rosin Fluxes

There are three types of rosin fluxes: (1) nonactivated; (2) mildly activated; and (3) activated. In *nonactivated rosin,* also known as "water-white," the active ingredient is abietic acid, which becomes mildly active at 177–316°C (350–600°F). Many nonactivated rosins are natural in origin, including "wood rosin" and "pine pitch rosin." The residue of such rosins is hard, nonhydroscopic, electrically nonconductive, and noncorrosive. Although it is not essential to remove residue with the flux, it is still best to do so. Warm to hot water works well.

Mildly activated rosins were developed to increase the fluxing action of natural rosins without significantly altering the noncorrosive nature of the residue. Such rosins are commonly used for soldering military and other high-reliability electronic products.

Activated rosins, on the other hand, are more active (through the use of additives to the natural rosin) and should be restricted to use in commercial electronics, where residue can be completely removed.

Examples of rosin fluxes are given in Table 8.14.

8.6.3 Organic Fluxes

Organic fluxes, while less chemically active or aggressive than the organic types, are effective at soldering temperatures of 90–320°C (200–600°F). They consist of organic acids and bases and, often, certain of their derivatives, such as hydrohalides. Examples are listed in Table 8.14. Organic fluxes are active from just below the soldering temperature into the soldering range, but the period of their activity is short because of the inherent susceptibility to thermal decomposition. When used properly (i.e., they are properly matched to the base metal(s) and are used in proper amounts), residues are fairly benign and water soluble.

8.6.4 Inorganic Fluxes

Inorganic fluxes consist of inorganic acids and salts that are extremely chemically aggressive and highly corrosive. Inorganic fluxes are used to best advantage where conditions concerning the base metal(s) and/or the environment require rapid and highly active fluxing action (i.e., extremely tenacious oxides or tarnish layers on metals and alloys considered to have poor solderability). These fluxes are usually formulated to provide activity and stability over the entire soldering temperature range. One distinct disadvantage of these inherently aggressive fluxes is that the residue they produce after reacting with the contaminating layer, if not removed, can cause severe corrosion at the joint. Examples of some important inorganic fluxes are listed in Table 8.14.

The key to all flux selection and use is this two-part "rule"—Select a flux that is as aggressive as needed to do the job, but no more, and use only as much flux as absolutely necessary to accomplish the needed cleaning, no more.

8.6.5 Special Fluxes

"Reaction fluxes" are a special group of fluxes used for soldering aluminum and its alloys. Decomposition of the flux when it is heated provides a metallic film on the surface of the aluminum in place of the oxide film. Soldering is then preformed to this metallic film, for which wetting and spreading of the molten solder occurs more easily.

8.6.6 Physical Forms of Fluxes

Flux in most of the aforementioned categories is available in single or multiple cores in wires or as liquids, or as pastes or creams, dry powders, or compacted preforms.

Table 8.14 Rosin, Organic, and Inorganic Solder Fluxes

	Typical fluxes	*Vehicle*	*Use*	*Temperature Stability*	*Tarnish Removal*	*Corrosiveness*	*Post-Solder Cleaning Methods*
			Inorganic				
Acids	Hydrochloric, hydrofluoric, orthophosphoric	Water, petrolatum paste	Structural	Excellent	Excellent	High	Hot-water rinse and neutralize; organic solvents; degrease
Salts	Zinc chloride, ammonium chloride, tin chloride	Water, petrolatum paste, polyethylene glycol	Structural	Excellent	Excellent	High	Hot-water rinse and neutralize, 2% HCl solution, hot-water rinse and neutralize; organic solvents; degrease[a]
Gases	Hydrogen forming gas, dry HCl	None	Electrical	Excellent	Very good at high temperatures	None normally	None required
			Organic: Nonrosin Base				
Acids	Lactic, oleic, stearic, glutamic, phthalic	Water, organic solvents, petrolatum paste, polyethylene glycol	Structural, electrical	Fairly good	Very good	Moderate	Hot-water rinse and neutralize; organic solvents; degrease[a]
Halogens	Aniline hydrochloride, glutamic acid hydrochloride, bromide derivatives of palmitic acid, hydrazine hydrochloride, or hydrobromide	Water, organic solvents, polyethylene glycol	Structural, electrical	Fairly good	Very good	Moderate	Hot-water rinse and neutralize; organic solvents; degrease[a]
Amines and amides	Urea, ethylenediamine, monoethanolamine and triethanolamine	Water, organic solvents, petrolatum paste, polyethylene glycol	Structural, electrical	Fair	Good	Moderate	Hot-water rinse and neutralize; organic solvents; degrease[a]
			Organic: Nonrosin Base				
Acids	Lactic, oleic, stearic, glutamic, phthalic	Water, organic solvents, petrolatum paste, polyethylene glycol	Structural, electrical	Fairly good	Very good	Moderate	Hot-water rinse and neutralize; organic solvents; degrease[a]

Halogens	Aniline hydrochloride, glutamic acid hydrochloride, bromide derivatives of palmitic acid, hydrazine hydrochloride, or hydrobromide	Water, organic solvents, polyethylene glycol	Structural, electrical	Fairly good	Very good	Moderate	Hot-water rinse and neutralize; organic solvents; degrease[a]
			Organic: Nonrosin Base				
Amines and amides	Urea, ethylenediamine, monoethanolamine and triethanolamine	Water, organic solvents, petralatum paste, polyethylene glycol	Structural, electrical	Fair	Good	Moderate	Hot-water rinse and neutralize; organic solvents; degrease[a]
			Organic: Rosin Base				
Rosin, superactivated	Rosin or resin with strong activators	Alcohols, organic solvents, glycols	Structural, electrical	Fair	Very good	Moderate	Water-base detergents; isopropanol; organic solvents; degrease[a]
Activated (RA)[b]	Rosin or resin with activator	Alcohols, organic solvents, glycols	Electrical	Fair	Good	Only to critical electronics	Water-base detergents; isopropanol; organic solvents, degrease[a]
Mildly activated (RMA)[b]	White-water rosin with activator	Alcohols, organic solvents, glycols	Electrical	Poor	Fair	None	Water-base detergents; isopropanol; organic solvents; degrease[a]
Nonactivated (water-white rosin) (R)[b]	White-water rosin only	Alcohols, organic solvents, glycols	Electrical	Poor	Weak	None	Same as activated rosin but normally does not require post-cleaning

[a] For optimum cleaning, follow by wash with demineralized or distilled water.
[b] Follows Federal Specification QQ-S-571 or MIL-F-4265

Reprinted with permission from H. H. Manko, *Solders and Soldering*, McGraw-Hill, 1964, pages 28–29.
Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, pages 346, 348, Table 9.12, 1993, with permission of Elsevier Science, Burlington,
MA.

Selection of the form of the flux depends on the joint design, base material(s), and particular process to be used.

8.6.7 Fluxless Soldering and Soldering Atmospheres

There is growing interest in being able to solder without requiring fluxes. The reason is primarily to eliminate the need for subsequent cleaning with chlorinated hydrocarbon or chlorofluorocarbon (CFC) solvents, but also to eliminate the need for flux application, often by screening solder paste onto areas where there are joints to be soldered. One fluxless approach employs a laser to remove contaminants and light oxide or tarnish layers by ablation. This is known as "laser ablative fluxless soldering" (LAFS), and works by causing the brittle ceramic oxide or tarnish layer to pop off under the tensile stress caused by the differential rates of thermal expansion between it and the underlying base metal. The ceramics tend to have lower CTEs than metals.

Other approaches use gaseous forms of flux that sweep away any residue. Citric and formic acid vapor have been used successfully. There are also some proprietary approaches that have been developed, one of which (by Rockwell International) was called ROSA, which relied on some exotic chemical reduction reactions that resulted in gaseous reaction products.

8.7 JOINT DESIGNS AND JOINT PROPERTIES FOR SOLDERING

8.7.1 Solder Joint Designs

The selection of a solder joint design for a specific application depends not only on the service requirements of the assembly but also on the heating methods to be used, the fabrication techniques before soldering, the number of items to be soldered, and the soldering process to be used.

When the service requirements of a joint are severe, it is generally necessary to design it so that the strength of the joint is equal to or greater than the load-carrying capacity of the weakest member of the assembly. Solders have inherently low strength compared to the materials that are generally being soldered, so the soldered joint should be designed to avoid dependence on the strength of the solder alone. Required strength can be provided in the joint by shaping the parts to be joined so they engage and interlock and require the solder only to seal and stiffen the assembly. This is generally true whether the soldered joints are intended for use in mechanical systems or electrical systems.

Two basic types of designs are used for soldering mechanical as well as electrical assemblies, as shown in Figure 8.14: the lap joint and the butt joint (just as with brazing and adhesive bonding). The lap joint is by far the more common solder joint and should be applied wherever possible, since it offers joints of maximum strength by taking loading in shear. The strength of the joint varies with the size of the overlap and with out-of-plane peeling forces induced at the ends of the overlaps by bending (see Subsection 4.6.4). The tendency toward peeling can be resisted by going to more elaborate double-lap and strapped-lap designs, the latter of which is good for sealing.

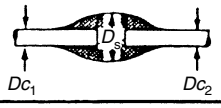
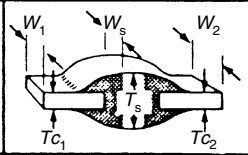
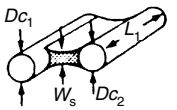
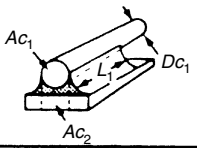
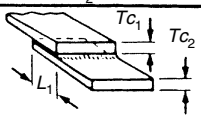
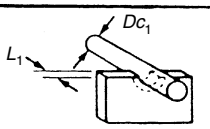
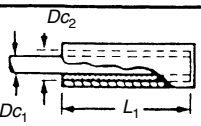
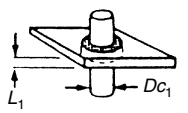
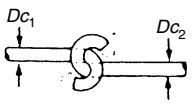
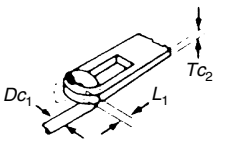
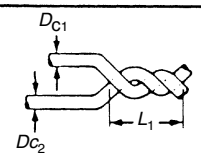
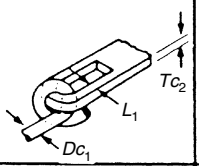
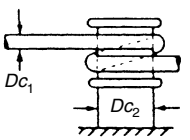
Group 1—No mechanical security prior to soldering						
Butt connections						
No.	Type	Diagram	Controlling formula	Conditions	Fixtures	Current
1	Round to round		$D_s = \sqrt{\delta Dc_1}$	$\rho c_1 \geq \rho c_2$ $Dc_1 \leq Dc_2$	Yes	Small
2	Square to square		$Ds = \sqrt{\frac{4}{\pi}}\delta Tc_1$	$\rho c_1 \geq \rho c_2$ $Tc_1 \leq Tc_2$	Yes	Small
3	Rectangle to rectangle		$T_s = \delta Tc_1$	$\rho c_1 \geq \rho c_2$ $W_1 = W_2 = W_s$ $Tc_1 \leq Tc_2 \neq T_s$	Yes	Small
Lap connections						
1	Round* to round		$L_1 = \frac{\pi}{2}\delta Dc_1$	$\rho c_1 \geq \rho c_2$ $Dc_1 \leq Dc_2$ $W_s \geq \frac{Dc_1}{2}$	Yes	Large
2	Round to flat		$L_1 = \frac{\pi}{4}\delta Dc_1$	$\rho c_1 \geq \rho c_2$ $Ac_1 \leq Ac_2$	Optional	Large
3	Flat to flat		$L_1 = \delta Tc_1$	$\rho c_1 \geq \rho c_2$ $W_1 = W_2 = W_s$ $Tc_1 \leq Tc_2$	Optional	Large
4	Wire to post		$L_1 = \frac{1}{2}\delta Dc_1$	$\rho c_1 \geq \rho c_2$ Solder tillet $\geq \frac{Dc_1}{2}$	No	Medium
5	Wire to cup		$L_1 = \frac{1}{4}(\delta - 1)Dc_1$	$\rho c_1 \geq \rho c_2$	No	Large
6	Wire to hole		$L_1 = \frac{1}{4}\delta Dc_1$	$\rho c_1 \geq \rho c_2$	Optional	Medium

Figure 8.14 Schematics showing the four principal types of solder connections used in electrical assembly: butt connections, (*Continues*)

Group II—Partial mechanical security prior to soldering						
Hook connections						
No	Type	Diagram	Controlling formula	Conditions	Fixtures	Current
1	Round to round		$Dc_1 = \frac{2}{\delta} Dc_2$	$\rho c_1 \geq \rho c_2$ $Dc_1 \leq Dc_2$ Hook $\geq 180°$	No	Large
2	Round to flat		$Dc_1 = \frac{1}{\pi\delta}(8L_1+4T_{c2})$	$\rho c_1 \geq \rho c_2$ $Ac_1 \leq Ac_2$ Hook $\geq 180°$	No	Medium
Group III—Full mechanical security prior to soldering**						
Wrap connections						
No	Type	Diagram	Controlling formula	Conditions	Fixtures	Current
1	Round to round		$L_1 = \frac{\pi}{2}\delta Dc_1$	$\rho c_1 \geq \rho c_2$ $Dc_1 \leq Dc_2$ $N > 1$	No	Large
2	Round to flat		$Dc_1 = \frac{8}{\pi\delta}(L_1+Tc_2)$	$\rho c_1 \geq \rho c_2$ $Ac_1 \leq Ac_2$ $N = 1$	No	Medium
3	Round to post		$Dc_1 = \frac{4N}{\delta} Dc_1$	$\rho c_1 \geq \rho c_2$ $Dc_1 < Dc_2$ $N \geq 1$	No	Large

Dc_1 – Diameter of smaller conductor
Ac_1 – Area of smaller conductor
S – Solder
W – Width
L_1 – Length of joint
T – Thickness
N – Number of Turns
δ – Resistivity Ratio $\frac{\rho_s}{\rho_{c1}}$
ρ – Resistivity (Microhm – cm)

*Use only when large conductor diameter is 3 to 4 times larger than small diameter; otherwise use round-to-flat lap-joint formula.

**In cases where loosening or breaking of the joint would result in a hazardous condition, mechanical security should be specified.

Figure 8.14 (*cont'd*) lap connections, hook connections, and wrap connections. (Reprinted from *Soldering Manual*, 2nd edition, Tables 4.2 and 4.3, pages 30 and 31, American Welding Society, Miami, FL, 1978, with permission.)

The butt joint is the simplest and weakest type of joint, as the area of soldered interface is limited by the cross-sections of the parts, which are often small in soldered assemblies. Loading usually results in pure tension, however, and this is good. A scarf joint is a butt joint with a larger cross-sectional area produced by cutting the joint at an angle through the thickness. In addition to increasing the cross-sectional area, the scarf converts tension loading into shear loading, which is usually advantageous in solders, as in brazes and adhesives.

For the best performance in mechanical applications, there are three primary attachment configurations that employ these basic connection types: (1) straight-through attachment; (2) clinched-lead attachment; and (3) surface mounting. The first two methods are referred to as "through-hole methods." Predominantly used in the past, through-hole joints still find application today. More and more, however, surface mounting methods are being used.

In *straight-through attachment,* component leads are inserted into holes drilled in the circuit board and either left straight or hooked or crimped slightly. Actual electrical connection is usually by manual, dip, or wave soldering. Plated-through holes are recommended if the printed wiring board has more than one layer, as such plating effects electrical interconnection between layers. The hook or crimp provides a reasonable mechanical component that reinforces the joint and helps prevent creep of the solder in service and, thus, eventual failure by carrying much of the loading itself rather than forcing the solder to carry it. In *clinched-lead attachment,* component leads are inserted into holes in the circuit board and are bent by wiping the protruding leads and soldering, or even by twisting the leads and soldering. Clinched-lead attachment is recommended for multiple-lead components such as integrated circuits, where greater lead strength is available, and in systems where the extra lead length will not adversely affect electrical performance. The added strength provided by the mechanical locking is significant to the joint's performance.

In *surface mounting,* component leads are attached to the circuit by soldering in a lap configuration. Surface mounting is the only attachment method that provides access to conductive joints from the component side, allowing components to be attached to both faces of the circuit board. Because components can be attached to both faces of the circuit board, surface mounting technology (SMT) allows maximum packaging density. Connection in SMT is by conventional or reflow soldering, or by adhesive bonding to eitherside or both sides of the circuit board. The mechanical integrity of surface-mounted soldered components is quite limited because there are no actual wire leads to act as springs between the device and the point of solder attachment to the board. Without any compliance being provided by leads, all of the loads, stresses, and strains associated with operation, whether mechanically or thermally induced, must be borne by the solder.[13]

When soldering is used principally for mechanical assembly, as opposed to electrical connectivity, different joint designs are required. Often, these joints involve larger bonded areas to reduce stresses and, occasionally, mechanical interlocks to carry some if not most of the loading. Examples of 21 methods that can be used to make solder joints, as

[13] One should keep in mind that solders, being low melting and soft, are not well suited to sustaining stress without experiencing either short-term plastic deformation or long-term creep.

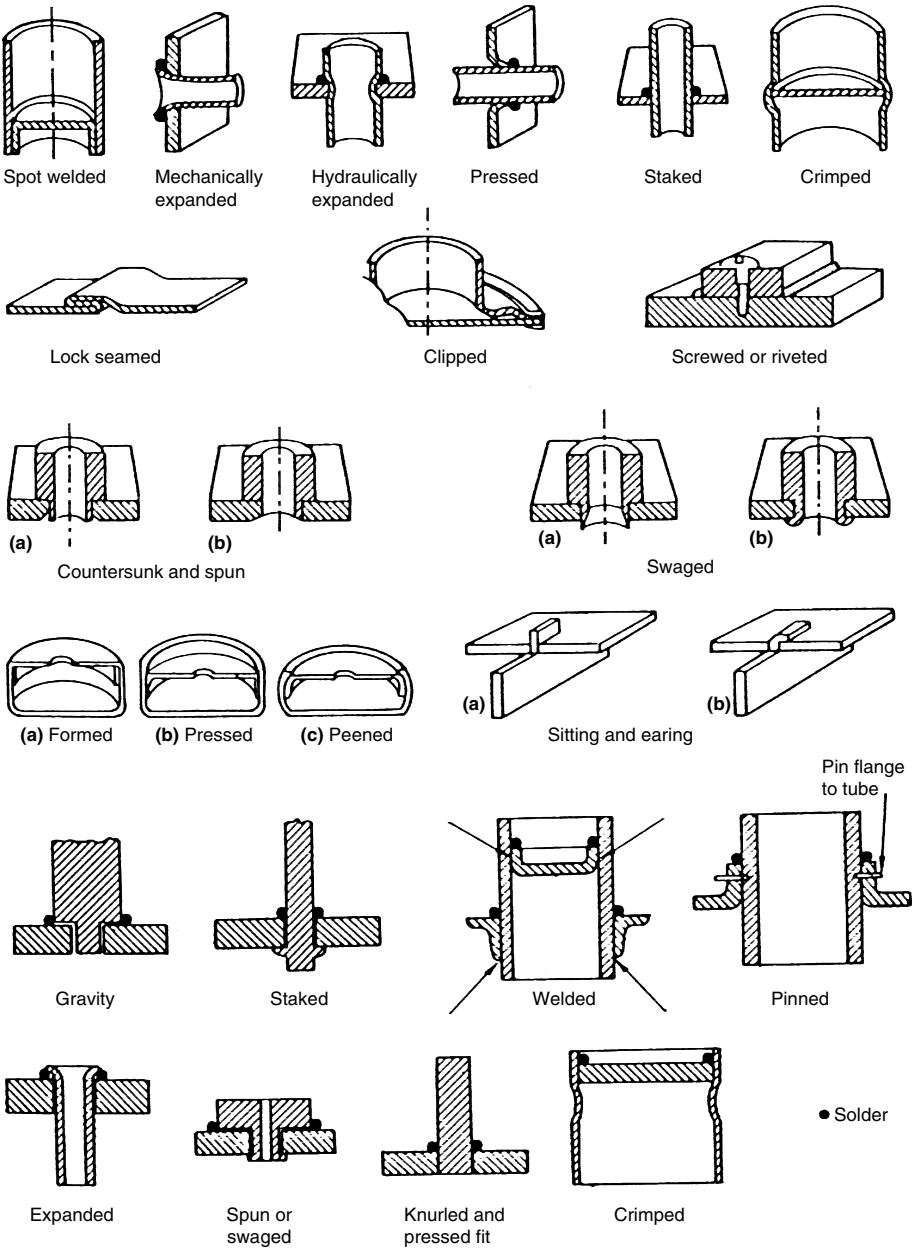


Figure 8.15 Schematic illustrations showing methods for making mechanical solder joints, as compiled by the American Welding Society. (Reprinted from *Solders and Soldering*, H.H. Manko, 2nd edition, Fig. 4.3 and 4.4, pages 142 and 143, McGraw-Hill Publishing, New York, NY, 1979, with permission.)

compiled by the American Welding Society, are shown in Figure 8.15, with more general approaches to provide full mechanical security before soldering shown in Figure 8.14.

Irrespective of the specific design of a joint, feeding of solder into the joint during soldering is a major consideration for proper execution of the process. As in brazing, joint clearance is a critical factor. As a rule, joint clearance should be 0.075 mm (0.003 in.) for optimum strength. In fact, the maximum capillary rise that is possible in a joint is directly related to the joint gap or clearance given by:

$$h = 2\sigma \cos \theta / d\rho g \tag{8.1}$$

where σ is the surface tension (in ergs or dynes), θ is the contact angle of wetting (in degrees), d is the capillary gap (in meters), ρ is the density of the molten solder (in kg/m^3), and g is the force of gravitational attraction (in m/s^2).

Factors in the joint design that relate to the flow of solder include (1) providing a suitable reservoir of molten solder; (2) providing a feed path to the capillary; (3) providing suitable capillary entrance and exit; (4) controlling the gap to provide a suitable capillary driving force; (5) balancing the mass in the joint to ensure even heating and to control flow; (6) providing a joint that is suited to the planned method of heating; and (7) providing enough freedom in the joint to prevent entrapment of flux or flux residue.

8.7.2 Solder Joint Properties

In general, the shear strength of soldered joints ranges from less than 7 to 49 MPa (1,000 psi to around 7,000 psi). Typical mechanical properties for a variety of soft solder alloys are shown in Table 8.15. The strength of solders generally increases with decreasing temperature (i.e., at lower homologous temperatures) and decreases with increasing temperature as creep becomes worrisome, often significantly. As an example, the ultimate tensile strength of 65/35 Sn/Pb solder increases from 52 MPa (7,260 psi) at room temperature to 96 MPa (13,720 psi) at $-180^\circ C$ ($-360^\circ F$). The effect of increased temperature on the shear strength of some solders is shown in Table 8.16.

8.8 SOLDERABILITY TESTING

8.8.1 General Description of Solderability Testing

The ability of a material to be wetted by molten solder is intimately related to its *solderability,* although there are some additional factors. Solderability depends partly on the inherent character of the base material involved, partly on the degree of cleanliness of the surface(s) to be soldered after the fabrication of the detail parts of the assembly, and partly on the aging[14] caused by environmental attack during storage.

[14] This is a different connotation of the term "aging" than used with heat-affected zone effects in precipitation-hardenable alloys. Here, it refers to the development of an oxide layer, not a second-phase precipitate.

Table 8.15 Some Mechanical Properties of Common Soft-Solder Alloys

	Alloy Composition %							*Melting Temp. °F*		*Tensile Strength*		*Shear Strength*	
No.	*Sn*	*Pb*	*Bi*	*In*	*Sb*	*Cd*	*Ag*	*Solidus*	*Liquidus*	*lb/in²*	*kg/cm²*	*lb/in²*	*kg/cm²*
1	8.3	22.6	44.7	19.1	...	5.3	...	...	117	5400	38.0	NA	NA
2	12.0	18.0	49.0	21.0	...	...	...	...	136	6300	44.3	NA	NA
3	13.3	26.7	50.0	...	...	10.0	...	...	158	5990	41.5	300[b]	2.1[b]
4	12.5	25.0	50.0	...	...	12.5	...	158	165	4550	32.0	NA	NA
5	11.3	37.7	42.5	...	...	8.5	...	160	190	5400	38.0	300[b]	2.1[b]
6	50.0	...	...	50.0	...	...	...	...	243	1720	12.1	1630[c]	11.5[c]
7	37.5	37.5	...	25.0	...	...	...	...	280	5260	36.9	4300[c]	30.2[c]
8	42.0	...	58.0	...	...	...	...	...	281	8000	56.2	500[b]	3.51[b]
9	...	15.0	...	80.0	...	...	5.0	...	314	2550	17.9	2150[c]	15.1[c]
10	...	...	...	100.0	...	...	...	...	314	515	3.6	890[c]	6.3[c]
11	70.0	18.0	...	12.0	...	...	...	302	345	5320	37.4	4190[c]	29.5[c]
12	63.0	37.0	...	...	...	...	...	...	361	7700	54.1	5400	38.0
13	70.0	30.0	...	...	...	...	...	361	367	7800	54.8	5000	35.2
14	60.0	40.0	...	...	...	...	...	361	370	7600	53.4	5600	39.4
15	50.0	47.0	...	...	3.0	...	...	365	399	8400	59.1	6850	48.2
16	50.0	50.0	...	...	...	...	...	361	417	6200	43.6	5200	36.6
17	...	50.0	...	50.0	...	...	...	...	419	4670	32.8	2680[c]	18.8
18	96.5	...	...	...	...	...	3.5	...	430	8900	62.7	4600	32.3
19	...	...	...	90.0	...	...	10.0	...	448	1650	11.6	1600[c]	11.2[c]
20	...	75.0	...	25.0	...	...	...	...	448	5450	38.3	3520[c]	24.7[c]
21	40.0	60.0	...	...	...	...	...	361	460	5400	38.0	4800	33.7
22	95.0	...	...	...	5.0	...	...	452	464	5900	41.5	6000	42.2
23	95.0	...	...	...	...	...	5.0	430	473	8000	56.2	NA	NA
24	20.0	80.0	...	...	...	...	...	361	531	4800	33.7	4200	29.5
25	...	90.0	...	5.0	...	...	5.0	...	554	5730	40.3	3180[c]	22.4[c]
26	...	97.5	...	...	...	...	2.5	...	579	4400	31.0	2900	20.4
27	1.0	97.5	...	...	...	...	1.5	...	588	4420	31.1	NA	NA
28	...	95.0	...	5.0	...	...	...	...	599	4330	30.4	3220[c]	22.6[c]

[a]Ultimate stress alloy alone, except as noted.
[b]Recommended working stress in joint.
[c]Ultimate stress in joint.
NA = Not available.
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Good solderability results from good wetting, which means the formation of a uniform, smooth, unbroken, adherent coating of still liquid solder on the base metal without the use of highly active fluxes. With poor solderability, poor wetting, nonwetting, partial wetting, or dewetting is observed. These terms refer to different degrees and sources of wetting problems. Poor wetting refers to a high contact angle between the molten solder and the substrate with the result that spreading is slow or hindered. Nonwetting refers to the extreme case where the angle of contact is essentially 180 degrees, and no wetting occurs at all (i.e., the molten solder just beads up). Partial wetting refers to wetting that has occurred over only a portion of the substrate surface, probably because some areas were not properly cleaned or were recontaminated after cleaning. Dewetting refers to the condition where wetting occurred successfully, and the molten solder spread but subsequently drew back, leaving ''islands'' of substrate devoid of solder. The origin of dewetting is complex but related to reactions that occur after wetting and spreading that change (i.e., raise) the surface energy locally.

Although there is no perfect test, the main methods for assessing the solderability or wettability of a base material for soldering are (1) the dip-and-look method; (2) the

Elongation, %	*Brinell Hardness*	*Electrical Conductivity % IACS*	*Electrical Resistivity, μΩ-cm*	*Expansion Coefficient μm/(in)(°F)*	*Specific Gravity*	*General Notes*
1.5	12.0	3.3	51.62	13.9	8.86	Expands, then shrinks to zero in 30 min.
50.0	14.0	3.0	57.47	12.8	8.58	Expands, then shrinks to zero in 60 min.
200.0	9.2	4.0	43.10	12.2	9.38	Expands to 0.0057 in/in permanently
30.0	25.0	3.1	55.61	NA	9.50	Nonelectrical solder for low-ambient temp.
220.0	9.0	4.3	40.38	NA	9.43	Shrinks to 0.0025 in/in, then expands to zero in 60 min.
83.0	4.9[d]	11.7	14.74	NA	7.74	Low vapor pressure; good for glass
101.0	10.2[d]	7.8	22.10	NA	8.97	Very good resistance to alkaline corrosion
200.0	22.0	5.0	34.48	8.3	8.72	Expands to 0.0007 in/in, then shrinks to 0.0005 in/in
58.0	5.2	13.0	13.26	NA	8.20	Good for thin precoat on ceramics
41.0	Too soft	24.0	7.18	18.3	7.44	Expensive, bonds to nonmetallics
135.5	12.0[d]	12.2	14.13	NA	7.96	Good strength, low-cost indium alloy
28–30[e]	17.0	11.5	14.99	13.7	8.46	Used where pasty range is intolerable
20.0	17.0	12.5	13.79	12.0	8.17	Good pretinning alloy
27–40[e]	16.0	11.5	14.99	13.3	8.52	Good electrical-grade solder
29.0	15.6	9.6	17.96	NA	8.75	Similar to 50/50 Pb–Sn, resists creep well
38–98[e]	14.0	10.9	15.82	13.0	8.90	General-purpose solder
55.0	9.6[d]	6.0	28.74	NA	9.14	Very good resistance to alkaline corrosion
73.0	40.0	14.0	12.31	NA	10.38	High-temp, electrical solder for instruments
61.0	2.7[d]	22.1	7.80	NA	8.10	Solders silver, fired glass, and ceramics
47.5	10.2[d]	4.6	37.48	NA	9.80	Very good resistance to alkaline corrosion
39–115[c]	12.0	10.1	17.07	13.9	9.28	Inexpensive utility solder
38.0	13.3	NA	NA	15.0	7.20	Lead-free, used in food equipment
30.0	13.7[f]	12.6	13.70	NA	NA	High-temp, electrical solder
22.0	11.0	8.7	20.50	14.7	10.04	Cheap solder for body work and plumbing
23.0	9.0[d]	5.6	30.79	NA	11.30	Tin-free indium solder
42.0	Too soft	8.8	19.50	NA	NA	Torch solder, poor corrosion resistance
23.0	9.5	NA	NA	NA	11.28	Slightly better corrosion resistance than no. 26
52.0	6.0[d]	5.1	33.80	NA	11.35	Zinc-free indium solder

[d]Modified Brinell hardness, using 100-kg load, $\frac{1}{2}$ min.

[e]Depends on specimen preparation.

[f]Vickers pyramid diamond.

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wetting balance method; (3) the globule method; (4) the rotary dip method; (5) the meniscus rise method; and (6) the timed solder rise method.

8.8.2 Wetting Balance Method

The *wetting balance method* is one of the most common and versatile and certainly most quantitative methods for evaluating solderability. In this method the specimen, which should be representative of the base material (i.e., alloy, condition, and geometric form), is suspended from a sensitive balance (typically a spring balance) and immersed endwise to a predetermined depth in molten solder at a controlled temperature. The resultant vertical force arising from buoyancy and surface tension as they act on the immersed test specimen is detected by a transducer. The plotted force trace is compared to one derived from a perfectly wetted specimen of the same material and dimensions.

There are five stages in the test, as shown in Figure 8.16. In the first stage, just before immersion, there are no vertical forces other than the downward force of gravity on the specimen. In the second stage, immediately upon immersion of the tip of the

Table 8.16 Shear Strengths (kg/mm^2) of Some Important Solders as a Function of Temperature

Alloy				*Temperature 20° C*		*Temperature 100° C*	
Sn	*Pb*	*Sb*	*Ag*	*Strain Rate 0.05 mm/min*	*Strain Rate 50 mm/min*	*Strain Rate 0.05 mm/min*	*Strain Rate 50 mm/min*
60	40			20	39	13	34
10	90			17	36	11	16
62	36		2	28	52	12	34
40	58	2		24	43	11	25
95		5		28	55	14	29
5	93,5		1,5	18	30	12	21

The indicated strain rate is the rate of movement of the beam of the testing machine; the solder gap between the ring and plug is between 0.005 and 0.25 mm.

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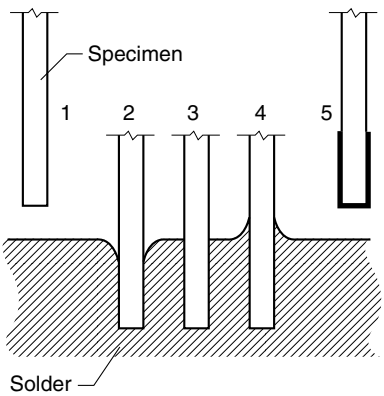

Figure 8.16 Schematic illustration of the operation of the wetting balance method for assessing solderability. (Reprinted from *Soldering in Electronics*, R.J. Klein-Wassink, Fig. 7.4, page 305, Electrochemical Publications Ltd., Port Erin, Isle of Man, British Isles, 1989, with permission.)

specimen, the surface of the molten solder bath is pushed down, the meniscus is still curved downward, and an upward force results from the surface tension. When wetting has occurred, in the third stage, the vertical force of surface tension goes to zero and only an upward buoyancy force based on the geometric shape and dimensions of the specimen and the density of the molten solder. In the fourth stage, the meniscus curves upward, and a downward force results from the surface tension of the molten solder "sucking" the specimen into the solder bath. The fifth stage occurs when the specimen is withdrawn from the bath and forces return to zero. Typical traces for various types or degrees of wetting are shown schematically in Figure 8.17.

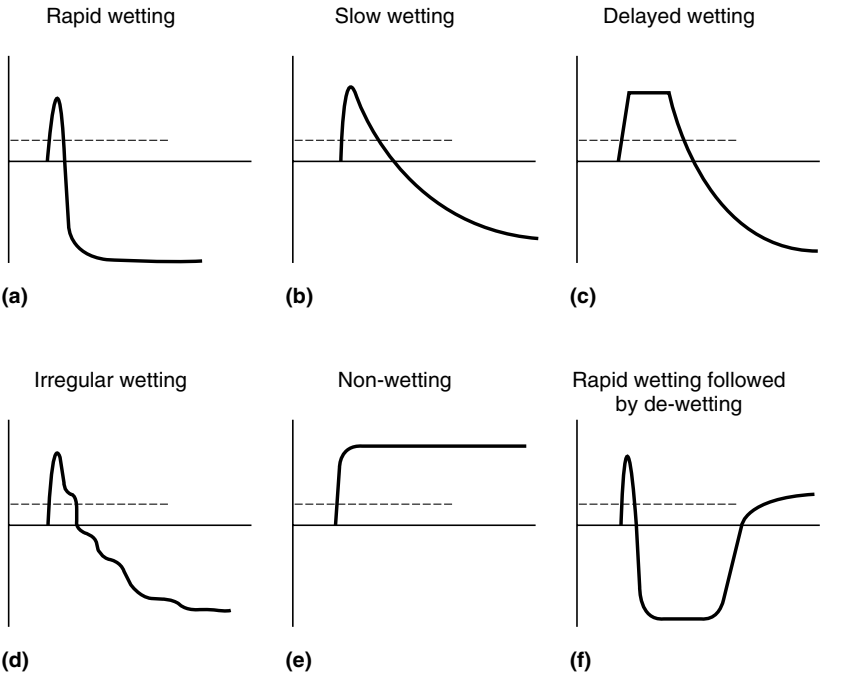

Figure 8.17 Schematic representation of typical traces from wetting balance tests for various wetting conditions, as shown. (Reprinted from *Soldering in Electronics*, R.J. Klein-Wassink, 2nd edition, Fig. 7.8, page 311, Electrochemical Publications Ltd., Port Erin, Isle of Man, British Isles, 1989, with permission.)

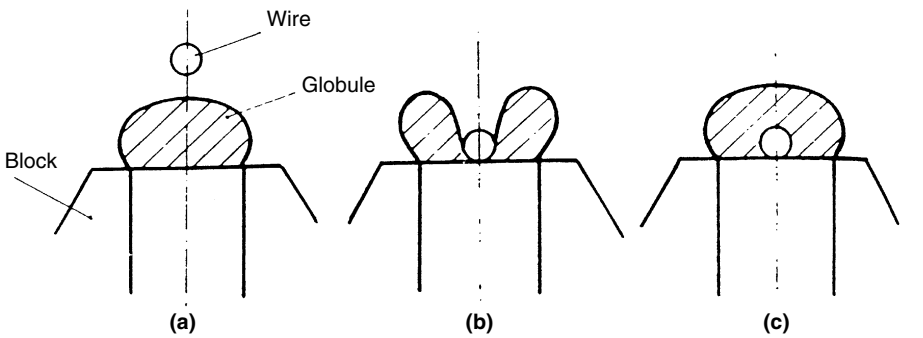

Figure 8.18 Schematic illustration of the globule method for assessing solderability. (Reprinted from *Soldering in Electronics*, R.J. Klein-Wassink, 2nd edition, Fig. 7.17, page 322, Electrochemical Publications Ltd., Port Erin, Isle of Man, British Isles, 1989, with permission.)

8.8.3 Globule Method

The longest established method for assessing solderability or wettability (with the possible exception of assessing spreading, below) is the *globule method*, developed by Philips-Einhoven in the Netherlands. The method measures the time required for molten solder at the soldering temperature to wet a circular wire of the base metal pressed into a molten globule of the solder (see Figure 8.18). The solder globule on the end of an iron post is bisected by the immersed wire test sample. The globule remains bisected until wetting occurs, at which point the impressed globule closes around the wire.

8.8.4 Spread Test of Solderability

One of the simplest and oldest tests of solderability is the spread test. In this test, a drop of the molten solder of known mass (by weighing) is placed on the surface of a flat plate or sheet of the base metal heated to the soldering temperature. The drop is allowed to wet and spread over the surface, producing an area of coverage. By measuring the area of coverage and knowing the volume of solder in the drop (from the mass divided by the density), one can obtain a semi-quantitative measure of how one solder versus another wets the substrate.

8.8.5 Other Solderability Test Methods

The other common methods for testing solderability are the dip-and-look, rotary dip, meniscus rise, and timed solder rise methods. In the *dip-and-look method,* which is absolutely the oldest and simplest method, the part is dipped into a molten bath of solder under controlled conditions (replicating production) and, after it is removed, the solder coating is inspected and evaluated for defects such as non-wetting, partial wetting, or dewetting. This evaluation is obviously highly subjective, but the test actually yields useful results, giving information on inherent wettability of a base metal (at least by comparison to other base metals) and preparation techniques for cleaning the surfaces to be soldered.

In the *rotary dip method,* which was originally developed for printed wire boards to simulate wave soldering, a sample is placed in a holder and, by means of a rotating arm, is passed across the surface of a molten solder bath such that contact time is controlled. The test involves exposing samples for progressively longer times of contact until full wetting is achieved, if it ever is! This test, like the globule test, is semi-quantitative. In the *meniscus rise* and *timed solder rise methods,* the time for solder to wet a substrate is measured by observing the formation of a meniscus with the substrate (i.e., formation of a low contact angle).

In soldering, as in brazing and adhesive bonding, achieving good wetting is the key to producing sound joints. It is prudent to assess the wettability of the substrate to be soldered (or brazed or adhesive-bonded) by testing before production assembly is ever begun, working out all details to optimize the process.

SUMMARY

Soldering, like brazing, enables solid materials (e.g., metals, ceramics, intermetallics, glasses, and composites with these materials as their matrices) to be joined by causing molten filler to flow into and fill the space between properly gapped joint faying surfaces, and then to solidify without requiring or causing melting of the base material(s). The liquidus of the filler in soldering is below the solidus of the base materials *and* below 450°C (840°F), by convention. Wetting and spreading of the filler by capillary action are then critical to proper distribution of the solder. Solder joint strength arises from a combination of metallic or other primary bonding (as the natural consequence of atoms seeking a stable electron configuration), as well as a contribution from mechanical interlocking between the filler and microscopic asperities on the base material surfaces that depends for its magnitude on the base material. The principal reasons for soldering are to provide electrical connectivity and conductivity and/or leaktightness or hermeticity, as opposed to providing mechanical strength. The low temperature of the process minimizes thermal damage to substrates, allows many joints to be made at once, and permits disassembly by desoldering. But the inherent low melting point of solder alloys restricts their inherent strength, and leads to loss of strength since most temperatures of service represent high fractions of the solder's absolute melting temperature.

Soldering depends critically on the wetting or solderability of the substrate by the solder at the soldering temperature. Precleaning and the use of fluxes are necessary to ensure proper wetting. After soldering, any residue from fluxes must be removed to avoid corrosion of the substrates, degradation of electrical conductivity, or shorting.

Soldering processes differ in their source of heat, by whether heating is localized at the joint or general over the entire assembly, and whether a particular process is intended to be practiced in a manual or in an automated mode. Major processes closely parallel brazing, and include iron, torch, dip, wave, oven, resistance, induction, and infrared embodiments. Modern soldering for electronic assembly often uses reflow methods in which preplaced solder is simply remelted to accomplish joining. All processes require the use of fluxes to help remove organic and oxide contaminants from the surfaces of the base metals being joined to facilitate wetting. Fluxes vary in chemical aggressiveness or activity, depending on the need, ranging from nonactivated rosin, mildly-activated rosin, or strongly activated rosin, to aggressive organic acids and bases, to highly aggressive inorganic acids or salts.

Solders are low-melting metals or alloys designed to be fluid at the soldering temperature. Most solder alloy systems exhibit eutectics. Ternary additions are often made to eutectic binaries to alter the eutectic temperature or increase fluidity by increasing the proportion of liquid in liquid–solid mixtures at the soldering temperature. Important alloys are Sn-Pb (the most common and diverse), Sn–Sb, Sn–Ag, Sn–Zn, Cd–Ag, Cd–Zn, Zn–Al, Bi-based very low melting "fusible" alloys, and In alloys. There is growing pressure to find effective Pb-free solders for environmental reasons.

Solder joints differ for mechanical and electrical assemblies, but all rely on some degree of mechanical interlocking between joint elements to provide strength, and all attempt to minimize loading of the inherently low-strength solder proper. Creep and

attendant thermomechanical fatigue are particular problems that limit the life of soldered joints, since the service temperature is frequently high compared to the absolute melting point of the solder.

To assess the solderability of a base material, various testing methods are used to quantify the degree of wetting that can be achieved. Principal methods include wetting balance, globule, rotary dip, meniscus rise, and timed solder rise.

QUESTIONS AND PROBLEMS

1. Define the process of soldering and compare it to the processes of (a) fusion welding, (b) brazing, (c) non-fusion welding, and (d) adhesive bonding. Include similarities and differences.
2. How are the processes of soldering, brazing, and adhesive bonding similar in terms of the way adhesion is achieved? What are some subtle but important differences between the role of chemical forces and the role of physical forces in bond formation during joining?
3. Compare the relative strength of the joints and the filler materials and base materials, as appropriate ratios, for several examples each of soft-soldering, brazing, and adhesive bonding. Is there much difference? Why or why not?
4. What is the "solderability" of a base material? What inherent properties of the base metal contribute to good solderability? What inherent properties of the base material contribute to poor solderability? What role does the solder play in the relative solderability of two different solders on the same base material?
5. What are two fundamental ways of improving the solderability of base material with inherently poor solderability? What are the relative advantages and disadvantages of one approach over the other?
6. What is "aging" as it pertains to soldering and solderability? Explain why aging is particularly problematic in typical manufacturing/production environments. What could be done to minimize these problems?
7. How is a specific solder selected for a particular application? What are considerations related to the base materials involved in the joint? What about the role of the soldering process in selecting a solder?
8. Why is pre-cleaning so important in soldering? What various steps are typically involved in pre-cleaning? What is "pre-coating" and why is it used? Does "pre-coating" have any analog in adhesive bonding? If so, what? Does it have any anolog in fusion welding? If so, what? (This part is tough!)
9. What is "solder residue," why is it a concern, and how can it be handled? What is "flux residue," why is it a concern, and how can it be handled?
10. What are the special considerations if dip or oven soldering is to be performed? What are the advantages of these processes over many other processes that make the problems worth trying to overcome or deal with?
11. What is meant by "reflow soldering"? Give some examples of reflow soldering processes or methods. Give some ways of making certain that solder will be precisely where it needs to be for reflow soldering.

12. For a typical binary solder alloy exhibiting eutectic and terminal phases with limited solid solubility, describe how solidification would progress as an alloy with a solute content lower than the solubility limit of its terminal solid solution phase was cooled from the melt. Make a reasonably accurate sketch of the phases and phase arrangement at several points during solidification, including (a) just above the liquidus, (b) just below the liquidus, (c) just above the solidus, (d) just below the solidus, and (e) at room temperature.
13. Referring to Problem #12, describe how solidification would progress if the solute content of the solder exceeded its solubility limit in the terminal solid solution phase but was less than the eutectic composition. Again, make reasonably accurate sketches of the phases and phase arrangements for the temperatures given in Problem #12.
14. What is the effect of substituting Sb for all of the Sn in an Sn–Pb solder? What is the effect of substituting Sb for all of the Pb in an Sn–Pb solder?
15. Why is Ag added to an Sn–Pb solder? Why is Ag sometimes used to totally replace all of the Pb in an Sn-based solder?
16. What benefits are derived from Cd-based solders? What limitations exist for these solders?
17. What is meant by a "fusible alloy"? Give four examples of situations in which such alloys are used, other than as solders.
18. What are the particular benefits of In-based solders? What is it about In that allows these solders to have their most notable feature? (Hint: look up the surface energies of Sn, Pb, and In, and consider these in your answer.) (This is a tough one!)
19. Discuss the three broad classifications of fluxes used in soldering. Are fluxes always required in soldering? If so, why? If not, why not?
20. What factors must always be taken into account when designing joints for soldering? What special factors must be taken into account in joints to be used in mechanical versus electrical assemblies?

Bonus Problems:

A. Look into how solidification actually takes place at the eutectic composition of a binary solder alloy like that in Problem #12, explaining what it is that tends to lead to the formation of alternating lamella in the eutectic constituent.
B. Consider how you go about finding Pb-free alternatives for soft-soldering. Think about the following: (1) melting point, (2) solubility with likely binary solutes, (3) wetting behavior (based on comparisons of surface energies), and (4) toxicity. (Hint: recognize that the following are the low-melting metallic elements in the periodic table: Hg, Ga, Bi, Cd, Sb, Pb, Sn, Zn, In.)

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Chapter 9

The Basic Metallurgy of Welding, Brazing, and Soldering

9.1 IMPORTANCE OF METALLURGY TO WELDING, BRAZING, AND SOLDERING

The process of joining materials by welding (and its subclasses of brazing and soldering) involves the application of heat to aid in the formation of atomic bonds that create the joint and hold the structural assembly together. As described in Chapter 6 on the process of welding, this heat may or may not be intense enough to cause melting of the parent or base materials and/or a compatible filler material. When it does cause melting of the base material(s) and any filler material, the process is referred to as ''fusion welding.'' When it does not cause melting of the base material(s) or any filler or intermediate material that may be used, it is referred to as ''non-fusion welding,'' and it may or may not involve heat to allow the process of weld formation to occur with less energy or more rapidly. When only a filler material is melted, and the base materials are not, the process is called ''brazing'' or ''soldering,'' depending solely on the melting temperature of the filler (i.e., above 450°C (840°F) for brazing, below 450°C (840°F) for soldering). The processes of brazing and soldering as subclasses of welding were discussed in Chapters 7 and 8, respectively.

Whatever the level of heating during welding, brazing, or soldering, above a certain temperature that heat causes the base materials to undergo changes in state (e.g., from solid to liquid), structure (e.g., microstructure), or both. For crystalline metals and ceramics, these changes can be significant and can include melting, gas–liquid chemical reactions (e.g., oxidation or gas absorption), solidification, liquid–solid reactions (e.g., eutectic or peritectic formation), grain growth, recrystallization, polymorphic or allotropic solid state transformations, solid phase reactions (e.g., eutectoid formation), or phase dissolution or precipitation. Which changes actually occur depend on the level of heating, the composition of the material(s) being heated, the environment, previous thermal–mechanical processing of the material(s) being heated (e.g., cold working, heat treatment, etc.), time at temperature, and heating and cooling rates. As a result, many of the reactions or transformations that occur are quite

different from those expected from and predicted by equilibrium phase diagrams. Thus, the resulting structure and properties are often much different (maybe better, maybe worse!) than those expected and predicted.

This chapter takes a brief look at the effects of heating and subsequent cooling on the final structure of the newly created joint and its surrounding regions during the processes of welding, brazing, and soldering. First, the thermal cycles used to accomplish welding, brazing, and soldering are considered, and then the distribution of heat in the parts being joined and its general effect on the materials making up those parts is considered. Next, the transformations and reactions that can occur in the fusion zone of a weld or in the molten filler of a brazed or soldered joint are described. Then, the process of solidification of the melt is described in the most basic sense. Similarities and differences between the solidification of pure crystalline metals or ceramics and crystalline metallic or ceramic alloys are presented, with special emphasis on the effects of non-equilibrium. Next, reactions or transformations in the region of welded, brazed, or soldered joints just outside any region of melting (i.e., in the heat-affected zone) are described. Effects of heat in work-hardened, solid solution–strengthened, age-hardened, transformation hardened or hardenable, dispersion-strengthened, or sensitization-prone materials are considered. Finally, sources of defects in the melted and resolidified and heat-affected regions are presented, along with methods for testing susceptibility to such defects and properties of final joints.

It must be recognized that the material science that underlies welding, brazing, and soldering is about as complex as it gets, because these processes occur under non-equilibrium and involve combinations of mechanical, thermal, chemical, and possibly electrical phenomena. For this reason, this chapter is meant to serve as an overview—a primer—and is by no means intended to be complete, although it is entirely accurate. The processes are treated together because they all involve the same basic principles. So, understanding one goes a long way toward understanding another. The reader in need of more information on the metallurgy of welding, brazing, and soldering is referred to any of several excellent books on the subject listed in the bibliography at the end of this chapter.

9.2 WELDING THERMAL CYCLES AND HEAT FLOW AROUND WELDS

9.2.1 General Description of the Effects of Heat During Welding

All fusion welding, all brazing, and all soldering processes need heat to allow joints to be produced through the formation of atomic-level bonding. Most non-fusion welding processes either use heat to facilitate weld formation or generate heat in the process of forming a weld using pressure or friction. The greatest differences among these processes from the standpoint of heat and its effects are as follows: (1) the peak temperatures reached as a fraction of the base material's melting point (i.e., the homologous temperature), which is highest for fusion welding, lower for brazing, and still lower

for soldering[1]; (2) the rate of heating is generally highest for fusion welding; (3) the time at peak temperature tends to be shortest for fusion welding; and (4) the rate of cooling once the heating source is removed also tends to be highest for fusion welding, then brazing, and finally soldering. Three things are essential to remember:

1. The rate of heating is important primarily in the ways in which it (a) causes heat to concentrate at the point of energy deposition, (b), as a result, gives rise to thermally induced local stresses and strains, and (c) in the way it shifts transformation temperatures upward slightly.
2. Time at peak temperature is particularly important, as all reactions that involve diffusion (as most do!) take time. (Examples are dissolution of gases from the atmosphere into the molten metal, oxidation of the molten or hot metal, and, in the solid state, the degree of phase dissolution or precipitation.)
3. The rate of cooling once the heat source has passed by or been terminated (a) causes phase transformation temperatures to be depressed from their equilibrium values, possibly to the extent that (b) certain liquid-to-solid and, much more often, solid-state transformations are suppressed or bypassed entirely. (The best examples are found in the iron–carbon system, in which steels cooled from their elevated temperature single solid phase austenitic region can be caused to avoid normal, near-equilibrium transformation to pearlite to form either bainite or martensite, depending on how fast cooling occurs and how far conditions deviate from equilibrium.)

It is important to remember that for fusion welding processes, not all of the energy available in the source reaches the workpiece to cause desired heating and melting to produce a weld. Losses occur between the source and the workpiece (see Subsection 6.4.6). There are also losses from some sources used to braze or solder, but not from all, and never as great because the temperatures of these sources are lower than for most fusion welding processes. As a result, lower temperature sources are less prone to certain types of losses (e.g., radiation of light and heat). Obviously, losses for non-fusion processes are not really an issue.

Even after the net energy from the source is transferred to the workpiece as heat, not all that heat contributes to producing a weld or, to a lesser extent, to a braze or solder joint. If the entire workpiece is not heated (as it is in many brazing or soldering processes, as seen in Chapters 7 and 8, Sections 7.4 and 8.4, respectively), some is conducted away from the joint, raising the temperature of the surrounding base material and causing unwanted microstructural or geometric changes. This surrounding region is called the ''heat-affected zone,'' and effects are more severe for processes that rely on high peak temperatures to produce the joint. Some heat is lost in others ways, too, as by convection to the atmosphere.

[1] Since fusion is never the goal of heating, for non-fusion processes the lower the temperature at which welds can be formed using just pressure or just solid-state diffusion, the better. Precisely how high temperatures get during non-fusion welding varies greatly with the specific process, being lowest for a cold welding process and highest for friction welding or diffusion welding of refractory metals and alloys.

To focus the discussion somewhat for convenience, the effects of heat during fusion welding will be described, although what is described applies equally well to brazing and soldering to the degree that these cause the base materials to be heated above room temperature. In considering the effects of heat on melting and solidification in the region of melting and on transformations in the surrounding heat-affected zone, it is important to first consider how that heat is distributed. How that heat is distributed directly influences the efficiency of melting, the extent and nature of peripheral heating, and the rate of subsequent cooling. The extent of melting, in turn, directly affects the weld size and shape, the homogeneity through convection, the degree of weld shrinkage and attendant weldment distortion and, often, the susceptibility to defects. The extent of peripheral heating, in turn, affects the following: (1) development of thermally induced stresses acting on the solidifying zone (which contribute to hot cracking); (2) the rate of cooling in the solidifying zone (which controls solidification mechanics and structure); (3) the level of heating in the heat-affected zone (which can cause degradation of properties); (4) the rate of cooling in the heat-affected zone (which determines the final structure and properties in this zone); and (5) the degree and nature of distortion and/or residual stresses in the newly joined assembly.

For all these reasons, the final distribution of heat in fusion welds will be addressed in the following subsections. And remember, what is described for fusion welds applies equally well (albeit perhaps not as strongly) to other joining processes using heat, such as brazing, soldering, and certain non-fusion processes.

9.2.2 Welding Thermal Cycles and Their Effects

Welding, as well as brazing and soldering, causes material in the workpiece to experience a thermal excursion that varies in severity based on the specific process. For fusion welding processes, that excursion ranges from ambient temperature (which is normally the temperature of the indoor fabrication shop or outdoor construction site, but could be higher due to applied preheat) to above the liquidus temperature by some amount of superheating. As stated above, the severity of this excursion, in terms of the peak temperature reached and the times taken to reach that peak temperature and remain there, completely determines the effects on both the resulting microstructure for all material changes and the macrostructure in terms of dimensional integrity. The temperature-time excursion experienced by a weld (including both fusion and surrounding heat-affected zones) is the direct result of the temperature-time cycle applied by the process (i.e., the *welding thermal cycle*[2]).

Figure 9.1 shows hypothetical welding thermal cycles for a typical arc welding process and for a high energy density welding process superimposed on the same temperature-time axes. The plots represent what happens at a point on the weldment as a function of time, from just before the heat source acts on the point to after the heat source is removed from the point. Important aspects to note are as follows: (1) the temperature

[2] For brazed joints and soldered joints, their temperature-time excursions are determined by the corresponding *brazing* or *soldering thermal cycle*.

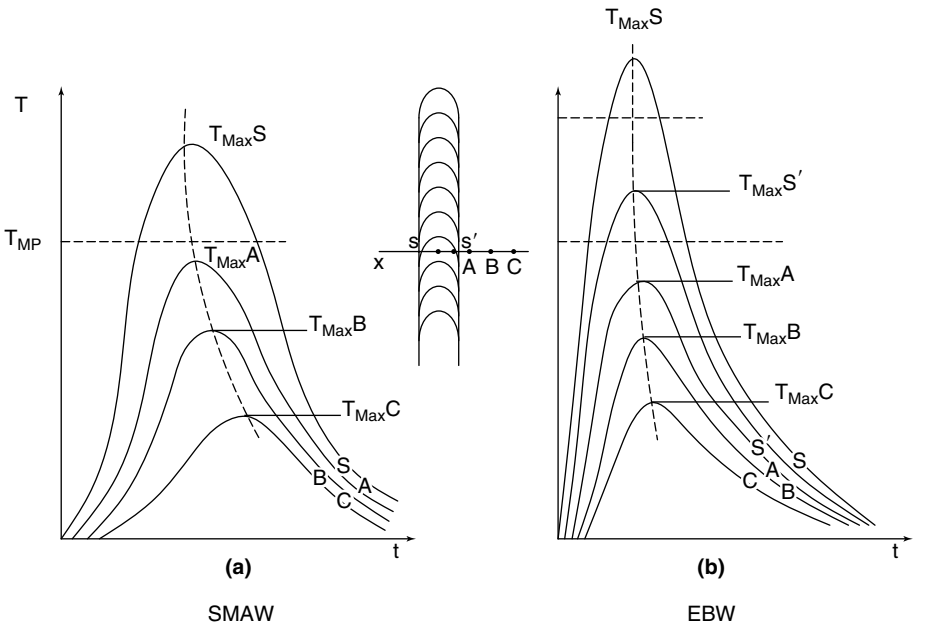

Figure 9.1 Schematic representations of typical welding thermal cycles for (a) a conventional arc welding process (e.g., SMAW) and (b) a typical high energy density process (e.g., EBW).

starts out at the ambient temperature of the environment prior to the arrival of a moving heat source (as in GMAW or LBW) or the startup of a stationary heat source (as in RSW); (2) the temperature rises very rapidly once the heat source acts on the point; (3) the temperature reaches a maximum or "peak" determined by the balance between the energy being inputted and all losses; (4) the temperature remains at that maximum only as long as the source remains on that spot (which, for a moving source, is only an instant); (5) the temperature cools back to the ambient level at a rate dependent on the thermal mass and thermal–physical properties of the material and any imposed cooling.

For conventional electric arc and resistance welding processes, the peak temperature can be much higher than the liquidus temperature of the base material being welded. This is typically only several hundred degrees Kelvin higher due to the short "dwell time" once melting is achieved. For high energy density processes (e.g., EBW and LBW), the superheat in the fusion zone can be much higher, often well over the boiling point of the base material. For lower intensity or lower temperature sources, as used in oxy-fuel gas welding and most brazing and soldering processes, the superheat above the liquidus is normally about 100°K for the gas welding process, 100°K for most brazing processes, and 30–50°K for most soldering processes. Superheat is needed to ensure that melting is complete, that some metallurgical cleansing action is allowed to occur from fluxes, and that sufficient fluidity is achieved to allow flow over fully wetted, still solid base material. Except in rare cases (e.g., to allow outgassing to prevent porosity

formation), the time over the liquidus temperature is kept as short as possible. This helps limit peripheral heating. Cooling of the newly formed joint and surrounding heat-affected zone is normally quite rapid (i.e., several hundred degrees Kelvin per second), near the solidification temperature. The only exceptions to this are when the cooling rate is limited to (1) below the critical cooling rate for martensite formation in steels, to prevent the formation of brittle, untempered martensite or (2) to prevent severe thermally induced stresses (and attendant distortion) due to nonuniform cooling.

Figures 9.2 and 9.3 show schematic temperature-time traces from three thermocouples located along a line perpendicular to a weld during passage of a moving welding heat source, and a schematic of the three-dimensional "heat solid"[3] that can be constructed from similar traces both parallel and perpendicular to a weld being made by a source moving at constant speed, respectively. Note that temperature drops rapidly from the peak temperature attained by the process as the distance perpendicular to the weld increases and as the distance behind the source once it has passed (or been shut off) increases. It is the temperature-time history within this heat-affected region that determines the effect on the base material surrounding the region of fusion (i.e., the heat-affected zone).

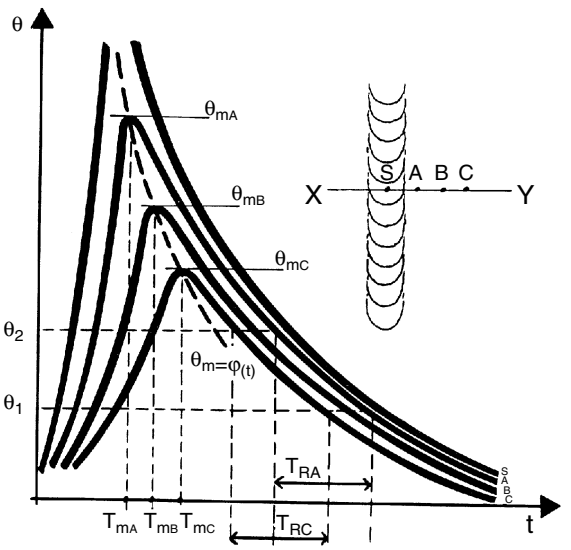

Figure 9.2 Schematic illustration of representative temperature-time traces for three points (A, B, and C) located along a line perpendicular to a weld during the passage of a moving welding heat source. Note the displacement of the occurrence of the peak temperatures and the quasi-steady-state nature of the cooling times in the lower portion of the curves. (Reprinted from *Fundamentals of Welding Metallurgy*, H. Granjon, Fig. 2.6, page 26, Abington Publishing, Woodhead Publishing, Cambridge, England, 1991, with permission.)

[3] The concept of a "heat solid," which helps visualize what is happening around a weld, was proposed by Portevin and Seferian (1935).

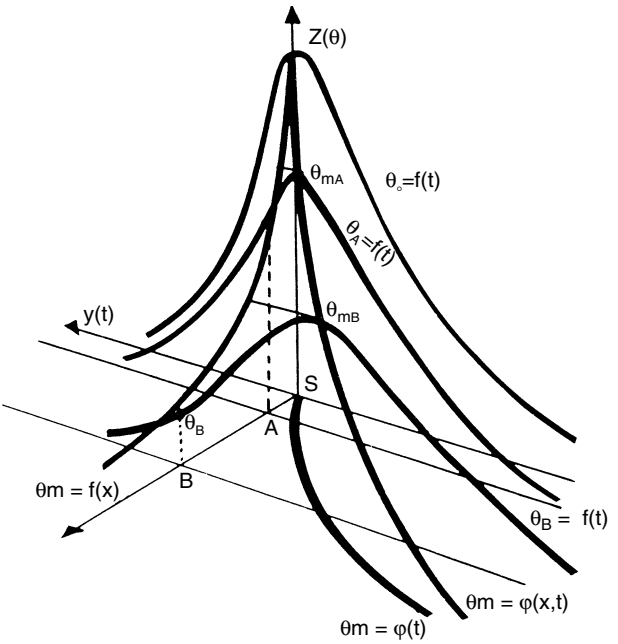

Figure 9.3 Schematic illustration of the ''heat solid'' suggested by Portevin and Seferian (1935), showing the distribution of the instantaneous temperatures around the heat source moving under quasi-steady state at the moment the source passes point S during movement along the line S_y. Temperatures are shown plotted only along S_z for each distance x for the weld line. (Reprinted from *Fundamentals of Welding Metallurgy*, H. Granjon, Fig. 2.7, page 27, Abington Publishing, Woodhead Publishing, Cambridge, England, 1991, with permission.)

9.2.3 Heat Flow Around Welds

It should now be clear that only some fraction of the total energy available in a heat source reaches a workpiece due to losses, and that once that net energy reaches the workpiece it produces a region of heating around the point of intended joining by a weld, braze layer, or solder layer. The distribution or flow of heat in a welded assembly is governed primarily by the time-dependent conduction of heat, which is expressed by the generalized equation of heat flow as:

$$\begin{aligned}\rho C \delta T/\delta t = {} & \delta/\delta x\ k(T)\delta T/\delta x + \delta/\delta y\ k(T)\delta T/\delta y + \delta/\delta z\ k(T)\delta T/\delta z \\ & - \rho C[V_x \delta T/\delta x + V_y \delta T/\delta y + V_z \delta T/\delta z] + Q\end{aligned} \tag{9.1}$$

where x is the coordinate in the direction of welding (in meters), y is the coordinate transverse to the welding direction (in meters), z is the coordinate normal to the assembly surface (in meters), T is the temperature of the assembly (in °K), $k(T)$ is the thermal conductivity of the base material (in J/m-s-°K) as a function of

temperature, $\rho(T)$ is the density of the base material (in kg/m^3) as a function of temperature, $C(T)$ is the specific heat of the base material (in J/kg-°K) as a function of temperature, V_x, V_y, and V_z are components of heat source velocity (in m/s), and Q is the amount of any internal heat generation (in W/m^3).

Whether this general equation needs to be solved for one, two, or three dimensions depends on the assembly and weld, braze, or solder joint geometry, including whether the weld is full- or partial-penetrating, whether it is parallel-sided or tapered (which depends mostly on energy deposition mode), and its relative plate thickness, as shown schematically in Figure 9.4. As two examples, a one-dimensional solution is acceptable for a moving source that creates a full-penetration, roughly parallel-sided weld in a thin sheet material, while a three-dimensional solution would be needed for a partial-penetration tapered weld made by a moving source in a very thick plate. Obviously, solving this equation becomes more difficult as the dimensionality of heat flow increases. Also, solution is especially difficult if one tries to properly account for the strong temperature dependence of the thermal–physical properties of most materials.

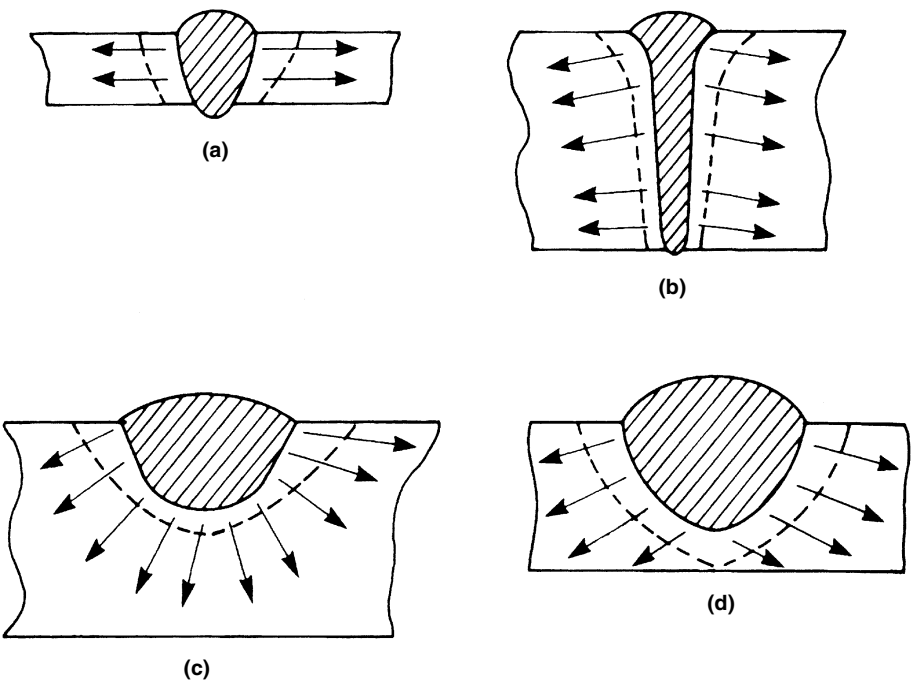

Figure 9.4 Schematic illustration of the effect of the size and shape (i.e., thermal mass) of a joint being welded, brazed, or soldered under different conditions on the dimensionality of heat flow. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 7.1, page 238, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

These complexities notwithstanding, theoretical analysis of the heat flow and resulting temperature distribution around a weld was attempted long before the advent of computers, with one of the first and most successful being by Rosenthal (1938, 1945, 1946). Rosenthal arrived at widely used and usually suitably accurate, simplified solutions for both the temperature distribution and the time-temperature distribution by using the following concepts: a quasi-steady state (when heat input from the source comes into balance with all losses); adoption of a coordinate system that moves with a constant-velocity heat source (to simplify source-velocity effects); solution from the fusion zone boundary with the unmelted base material (i.e., the melting point) outward (or downward in terms of temperature); and assumption of temperature-independent (i.e., constant) thermal–physical properties. Rosenthal's solutions, which apply to either a thin or a thick joint assembly, are as follows:

For a thin plate, the spatial distribution of temperature around the source is:

$$T - T_o = q/2\pi k \ \exp[-v\xi/2\alpha] \ K_o \ [vR/2\alpha] \tag{9.2}$$

while the temporal distribution at a particular point is:

$$T - T_o = q/v/d(4\pi k\rho C t)^{\frac{1}{2}} \exp[-r^2/4at] \tag{9.3}$$

where T is the temperature (in °K), T_o is the starting temperature (in °K), q is the heat input from the heat source (in J/m), k is the thermal conductivity (in J/m-s-°K), v is the velocity of the heat source (in m/s), $\xi = x - vt$ (where x is some fixed position along a line of welding, v is heat source velocity, and t is time after the source passes), α is the thermal diffusivity $= k/\rho C$ (in m^2/s), C is the specific heat (in J/kg-°K), K_o is a Bessel function of the first kind, zero order,[4] R is the distance from the heat source to a particular fixed point (in meters) $= (\xi^2 + y^2 + z^2)^{1/2}$, $r = y^2 + z^2$ (in meters), and d is the depth of the weld or thickness of the plate (in meters).

For a thick plate, the spatial distribution of temperature around the source is:

$$T - T_o = q/2\pi kd \exp[-v\xi/2\alpha] \ \exp[-vR/2\alpha]/R \tag{9.4}$$

while the temporal distribution of temperature at a particular point is:

$$T - T_o = q/v/2\pi kt \ \exp[-r^2/4\alpha t] \tag{9.5}$$

where T, T_o, q, k, d, v, ξ, α, R, r, and t are as before.

The forms of the spatial temperature distribution fields given in Equations 9.2 and 9.4 are schematically illustrated in Figure 9.5.

Since Rosenthal's outstanding early work, there have been numerous refinements to account for the weld pool and complexities of dimensionality. Modern computers and numerical methods allow much more precise calculations for much more realistic conditions, including effects of weld pool superheat, convection, and even temperature-dependent thermal–physical properties. The interested reader is referred to specialized treatments on weld heat flow, many of which are listed in Messler (1999).

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[4] Bessel functions of zero order, as well as other orders, can be found in any of many references on mathematical functions used in engineering.

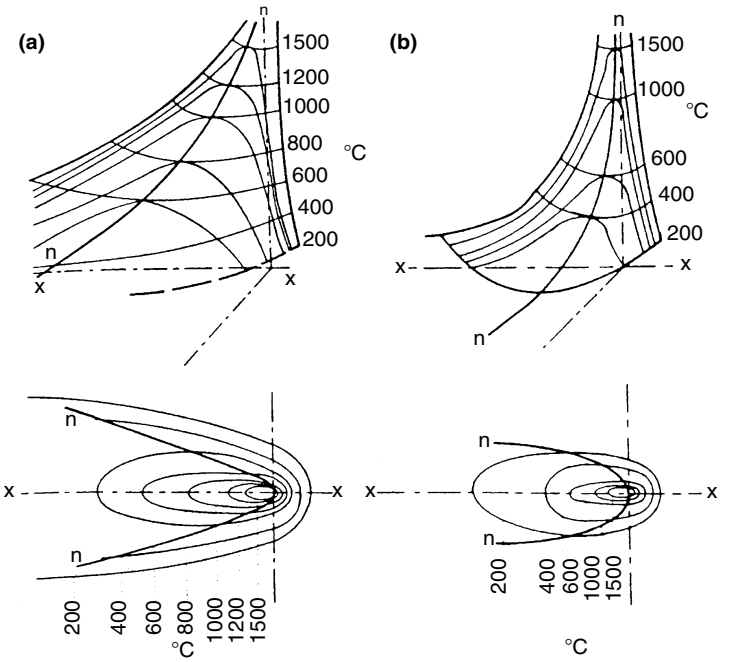

Figure 9.5 Schematic illustrations of plots of the temperature distribution field around a welding heat source (moving at quasi-steady state) in (a) thin and (b) thick plates. (Reprinted from *Introduction to the Physical Metallurgy of Welding*, K. Easterling, Fig. 1.18, page 21, Butterworth-Heinemann, Oxford, England, 1985, with permission from the heirs of K. Easterling.)

9.2.4 Microstructural Zones in Welded, Brazed, and Soldered Joints

As shown in Figure 6.7 for generic fusion and non-fusion welds, and again in Figure 9.6 for a fusion weld made in a hypothetical binary metal alloy, fusion welding produces several distinct microstructural zones in a crystalline material (whether pure or alloyed, metallic or ceramic). These different zones correlate with various transformations on appropriate phase diagrams, but only if adjusted for the non-equilibrium heating and cooling conditions that prevail during the real processes. Non-equilibrium leads to downward shifts in transformation temperatures on cooling, as well as to different phase distributions or even different microconstituents than appear under equilibrium. The best examples are the different lamellar spacing and morphologies that can occur in pearlite as it is formed at cooling conditions. Lamellar spacings decrease more and more as the conditions under which the pearlite is trying to form deviate more and more from equilibrium, finally causing the suppression of pearlite formation in favor of bainite formation (which, like pearlite, consists of alpha ferrite and cementite) at higher cooling

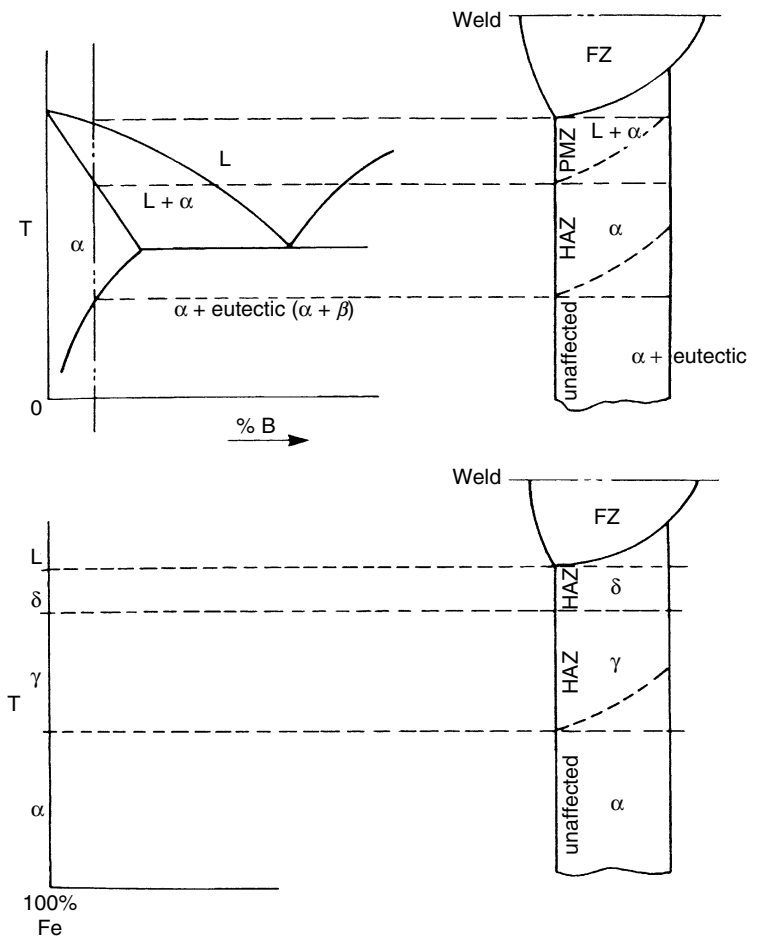

Figure 9.6 Schematic illustration showing the correlation between various microstructural zones in a fusion weld in a hypothetical alloy in the A–B binary system (a) with the corresponding hypothetical phase diagram (b). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 7.4, page 243, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

rates. Finally even bainite is suppressed in favor of martensite (which consists of a supersaturated metastable solid solution of carbon in alpha ferrite).

Figure 9.6 relates the zones formed to various transformations on the phase diagram for a hypothetical alloy system. Here, the fusion zone, FZ (or weld metal, WM, in a weld made with filler) is the portion of the weld that fully melted during welding by being heated to above the liquidus temperature for the alloy. Just inside this region, there is a region of the base metal that was heated to below the liquidus temperature but above the solidus temperature, so it was only partially melted. This zone is known as the partially melted zone (PMZ). Outside this zone is base metal

that was heated well above the ambient temperature, but below the solidus temperature. It constitutes the heat-affected zone (HAZ) and may actually consist of multiple subzones, depending on the mechanism by which the base material is strengthened. For the hypothetical alloys shown, there would be a subzone nearest the PMZ, and above the solvus temperature in which all of the β phase would be redissolved by the heat of welding (known as the "reversion zone"). Outside this, below the solvus temperature but well above the ambient temperature, there would be a subzone in which the β phase precipitate would have grown in what is known as the "over-aged zone." Naturally, there is no PMZ in a pure crystalline material because melting occurs at a discrete temperature, not over a range of temperatures. The so-called "weld zone" (WZ) in a thermally joined assembly consists of the FZ, any PMZ, and any HAZ.

For a brazed or soldered joint, there are also melt zones (made up of the filler alloy) and heat-affected zones in the base material heated high enough for long enough for changes to occur in the microstructure. Between these two (for both brazed and soldered joints) there is a reaction zone, formed when one or more of the elemental components of the liquid filler alloy reacts with one or more elemental components of the base material to form an intermetallic layer. This layer is formed by interdiffusion during the stage of the brazing or soldering process in which the filler is molten but the base material is solid. This intermetallic layer may or may not be necessary for forming a sound metallurgical bond, depending on the base material/braze or solder combination.

9.2.5 Simplified Equations for Approximating Welding and Weld Conditions

Solution of the generalized heat flow equation (Equation 9.1), to whatever degree of simplification is reasonable based on geometric conditions of the assembly being joined and for the particular joint as well as the material system(s) involved, can provide useful information on the size of various microstructural zones, such as the fusion zone and HAZ. It can also provide information on important conditions that prevailed in such zones that directly determine the resulting structure and, therefore, properties of those zones. However, even without solving what could be a complex heat flow equation (even when simplified!), it is possible to get good estimates of some of these important weld and welding conditions using various simplified equations or empirical formulae. The approximations given by these simplified equations are often "good enough," and that, after all, is what engineering is often all about.

So, here are simplified equations for the following to be calculated:

1. *Peak temperature* (T_p) attained at any point outside the fusion zone, allowing estimation of the width of the HAZ for any temperature known or suspected to be problematic to the particular base material.

2. *Solidification time* (S_t) *in the fusion zone*, from which the *solidification rate* (R) can be obtained as the reciprocal.[5]
3. *Cooling rate* (CR) at any point *in the heat-affected zone,* allowing determination of the formation of potentially embrittling microstructural constituents (such as untempered martensite in steels).

These simplified equations are as follows:

For peak temperature, T_p:

$$1/(T_p - T_o) = (2\pi e)^{0.5}\rho Chy/H_{net} + 1/(T_m - T_o) \tag{9.6}$$

where T_p is the peak temperature (in °K) attained at some point y (perpendicular to the weld FZ boundary, or the lateral edge of the fusion zone), T_o is the initial temperature of the weldment or assembly (in °K), ρ is the density of the base material (in kg/m^3), C is the specific heat of the base material (in J/kg-°K), h is the thickness of the base material at the joint (in meters), y is the distance from the fusion zone boundary (at which $y = 0$) (in meters), H_{net} is the net linear heat input (in J/m) to the weld $= \eta EI/v$ for arc welding (where η is the energy transfer efficiency, E is the welding voltage in volts, I is the welding current in amperes, and v is the welding velocity in m/s),[6] and T_m is the melting temperature of the base material.

For solidification time, S_t (in seconds):

$$S_t = LH_{net}/2\pi k\rho C(T_m - T_o)^2 \tag{9.7}$$

where L is the latent heat of fusion for the base material (in J/m^3), k is the thermal conductivity of the base material (in J/m-s-°K), ρ is the density of the base material (in kg/m^3), and H_{net}, C, T_m, and T_o are as above.

For cooling rate, CR (in °K/s):

$$CR = 2\pi k\rho C(h/H_{net})^2(T_c - T_o)^2$$

for thin plates requiring fewer than four passes, and;

$$CR = 2\pi k(T_c - T_o)^2/H_{net} \tag{9.9}$$

for thick plates requiring more than six passes, where k, ρ, C, H_{net}, and T_o are as before, and T_c is the temperature (in °K) at that point in the HAZ at which the cooling rate is being calculated.

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[5] Later, in Subsection 9.3.4, it will be seen how the simplified equations for estimating R (from S_t) and some estimate of the prevailing temperature gradient in the fusion zone (G) from the likely degree of superheat (which depends on the process employed) and the fusion zone width (which can be estimated using the dimensionless parameters developed by Christiansen *et al.*, 1965) might be used to predict substructure growth mode and scale using G/R and GR.

[6] For other welding processes, like oxy-fuel gas and laser beam, comparable energy inputs per unit of weld length can be used based on source energy.

9.3 CONSIDERATIONS IN THE FUSION ZONE

9.3.1 General Description of the Fusion Zone

The processes of melting and solidification that take place during fusion welding, as well as in the filler during brazing and soldering, are keys to the structure and properties of the welds, or braze or solder joints, that result. The features of fusion welds that have to be taken into account in the fusion zone itself are (1) the weld pool contains impurities or contaminants; (2) dilution of filler by the base material occurs; (3) there is considerable turbulence from convection and, therefore, good mixing in the main volume of the molten zone; (4) there is always a layer near the fusion zone boundary (known as the "unmixed zone") in which there is very little mixing because this layer is stagnant (i.e., free from convection flow); (5) the total volume of the molten material is small compared to the volume of the overall base material, which acts as a mold in which solidification takes place; (6) the compositions of the molten zone and the "mold" are compatible, being of either the same or similar and compatible basic materials; (7) there are large temperature gradients across the melt, giving rise to stresses and non-equilibrium transformations; (8) since the heat source usually moves, weld solidification is a dynamic process, dependent on the welding speed; and (9) in high heat input processes or with multi-pass welding in which the base material is preheated above the ambient temperature of the welding environment, temperature gradients and, hence, solidification behavior are affected.

For brazing and soldering, which both involve a molten layer rather than a "pool" of filler, (1) there are still impurities in the melt (albeit often fewer because the braze or solder melt is contained in overlapped joint elements, limiting exposure to the air); (2) there is less dilution of the filler by base material, except as occurs by diffusion versus substrate melting and intermixing; (3) there is very little significant turbulence (because the molten layer is thin and tends to be quite uniform in temperature across the melt); (4) there may actually be a "mixed" rather than an "unmixed" zone near the substrate, due to interdiffusion; (5) the volume of molten material is still small compared to the base material, so solidification occurs as it would in a "mold"; (6) the compositions of the molten filler and the base material(s) are obviously compatible, but never similar; (7) there are usually not very large gradients of temperature across the braze or solder; (8) solidification tends to be somewhat less dynamic because the heat source rarely moves the way it does in welding; and (9) there is seldom anything comparable to high heat input or multi-pass welding to affect solidification behavior. Hence, solidification of braze alloy and solders tends to be simpler than most fusion welds, with the preponderance of solidification occurring by a eutectic reaction.

The following subsections take a look at some of the more important considerations in the fusion zone of a weld (and, by analogy, braze or solder joints), including weld pool (or for braze or solder joints, melt) composition, weld pool size and shape (for welds only), and solidification of pure metals and alloys, respectively.

9.3.2 Weld Pool Composition

The composition of the weld pool in fusion welding (or the melt in brazing or soldering) is affected by many factors, including the composition(s) of the base material(s); the extent of base material melting or dilution in fusion welding (and mutual solubility in brazing and soldering); filler composition; cleaning or cleansing effects of fluxes; and degree of shielding and effects of dissolved gases. Figure 9.7a illustrates some of the various contributions to the composition of a fusion weld pool, while Figure 9.7b illustrates some of the contributions to the composition of the melts during brazing or soldering.

High temperatures during fusion welding in particular (and to progressively lesser extents for brazing and soldering) cause chemical reactions to occur between molten zones and the surrounding atmosphere unless proper protection is provided. Ductility and toughness are particularly degraded by the formation of brittle non-metallic compounds or inclusions. Fatigue strength especially is also degraded by entrapment of gas porosity. Various techniques can be used to protect the weld pool during fusion welding, and to protect brazes and solders during those thermal joining processes. For fusion welding, protection techniques include (1) inert shielding gases in GTAW, SMAW, FCAW, GMAW, and ESW (as well as in brazing or soldering using furnaces, induction, or infrared heating sources); (2) molten flux or slag in SAW and ESW (as well as in torch or dip brazing or iron, torch, dip, or wave soldering); (3) generated gas and slag in SMAW and FCAW; (4) vacuum in EBW (as well as vacuum brazing); and (5) self--protection in resistance welding, brazing, and soldering processes.

Despite all attempts to protect the molten metal from undesired reactions in fusion welding, brazing, and soldering, its composition is still subject to alteration by one or more of absorbed gases, metallurgical refinement by slag-metal reactions in fusion welding, and dilution by melted and mixed-in or simply dissolved base material.

Absorbed Gases

Absorption of gases from the surrounding air (which contains nominally 78%N_2, 20%O_2, $< 1\%CO_2$, and water vapor), from decomposed or dissociated contaminants (e.g., paints, oils, greases, organic solvents, and water), or from shielding atmospheres themselves can be a problem. Absorbed gases can lead to potent solid-solution hardening and embrittlement (e.g., from oxygen in Cu or Ni), unwanted stabilization of certain phases (e.g., austenite in stainless steels by nitrogen and the α-phase in Ti alloys by oxygen), formation of brittle phases (e.g., nitrides in Al alloys and hydrides in Ti), and gas porosity in most metals from oxygen, nitrogen, and hydrogen (from dissociated water) when the solubility limit is exceeded.[7] According to Sievert's Law, the equilibrium solubility of diatomic gases (only!) in a molten metal is proportional to the partial pressure of that diatomic gas in the surroundings to the one-half power (i.e.,

[7] The solubility of most gases in most molten metals increases with increasing temperature in the liquid and is much greater in the liquid than in the solid. Thus, as first cooling and then solidification of the melt occur, dissolved gases can be rejected as porosity, when bubbles are trapped in the solid.

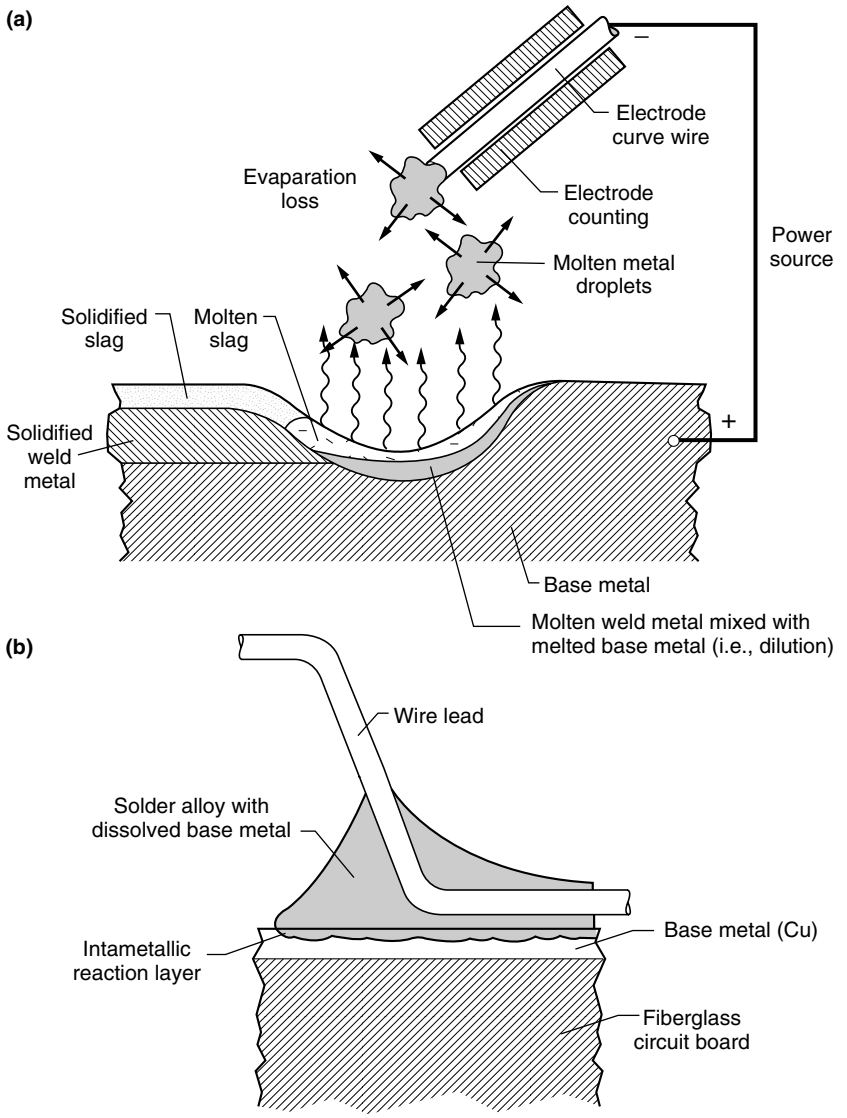

Figure 9.7 Schematic illustration of the various contributions to the composition of the weld pool of a typical SMA fusion weld (a) and a typical soldered joint of 96.3Sn–3.5Ag in pure Cu (b).

$K = [gas]P^{\frac{1}{2}}_{gas,\,diatomic}$). In actuality, more gaseous elements are found dissolved than this, as some gas dissolves in monatomic and ionic forms, as well. Which of the potential problems from absorbed gases actually occurs depends on the type and amount of gas absorbed and the metal and its alloying ingredients.

Metallurgical Refinement

Reactions between the molten slag formed by melting fluxes from coatings (e.g., in SMAW), cores (e.g., in FCAW), or other sources (e.g., dry granular flux in SAW or molten flux in ESW) and the molten weld metal help control the weld composition. Unwanted gases (like oxygen) as well as certain unwanted non-metallic elements (like S and P) are removed through oxidation/reduction processes similar to those that occur in the metallurgical refinement of metals and alloys during their production. The interested reader is referred to other sources for a treatment of slag-metal reactions in fusion welding. For brazes and solders, active fluxing agents are used much more to clean oxide and other tarnish layers that impede the wetting of base metals by molten fillers than to metallurgically refine or cleanse the molten filler.

Dilution

The composition of the molten metal in the pool of a fusion weld (or in the melt of a joint being brazed or soldered) can be altered by the base material. In fusion welding, the phenomenon is called "dilution," as it literally involves the dilution of any added filler by any and all base materials that are melted as part of the process. The factors that determine the degree of dilution at welding are heat input (as this affects the volume of base metal melted) and the shape of the joint preparation into which filler is being added. The effect is shown in Figure 9.7a. For brazes and solders, dissolution of some elemental component(s) from the base material usually occurs, even though the base material is not melted as part of the processes of brazing or soldering. Two examples are Cu being dissolved into 96.5wt.% Sn/3.5wt.% Ag solders until a ternary alloy saturated with Cu results, and Au plating applied to electrical components for corrosion protection being dissolved away by most Sn-based solders.

9.3.3 Fusion Weld Pool Size and Shape

Among fusion welding, brazing, and soldering, only fusion welding involves weld pools. The size and especially shape of the pool in a fusion weld affect the mechanics and kinetics of solidification and, therefore, the structure and properties of the resulting weld joint. The shape and especially size of the weld pool also affect the thermally induced stresses that act on the weld, leading to the formation of certain defects or to residual stresses or distortion. The shape of the pool and, to a lesser extent, its physical size are functions of material physical properties, welding speed, and welding power (i.e., voltage times current for electric processes) and can be obtained from the isotherms predicted by the solutions to the heat flow equation. Weld pool convection[8] as affected by process parameters and chemistry also has a strong effect on the shape of the melt. Figures 9.8 through 9.10 schematically illustrate

[8] *Convection* in a weld pool is the movement of the fluid caused by various forces acting on that fluid, including (1) gravity (acting on portions of the liquid with different densities due to composition or temperature); (2) any gradient of surface tension (caused by areas of high surface tension to pull on regions of low surface tension, arising from temperature or composition), also known as the "Marangoni force";

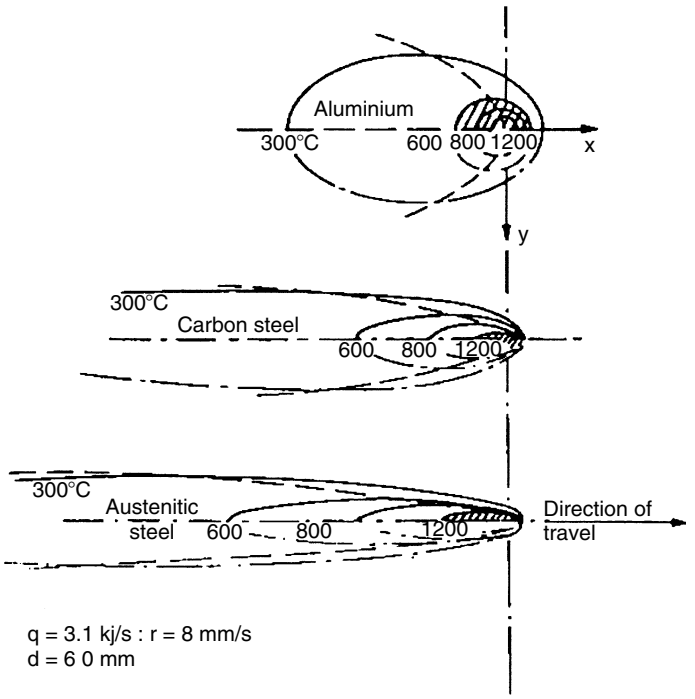

Figure 9.8 Schematic of the effect of material thermal–physical properties on the weld pool and HAZ size and shape. (Reprinted from *Rational Welding Design*, T.G.F. Gray and J. Spence, Newnes-Butterworth, London, England, 1975, with permission from Elsevier Science, Burlington, MA.)

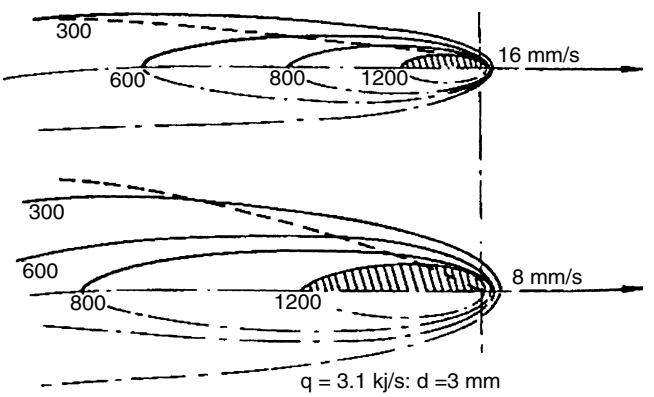

Figure 9.9 Schematic of the effect of welding speed on the weld pool and HAZ size and shape. (Reprinted from *Rational Welding Design*, T.G.F. Gray and J. Spence, Newnes-Butterworth, London, England, 1975, with permission from Elsevier Science, Burlington, MA.)

(3) Lorentz forces (arising from the interaction between the current in an arc or electron beam and the current induced in the conductive molten metal of the weld pool); and/or (4) the frictional or impingement force (arising from the momentum of particles in an arc or beam).

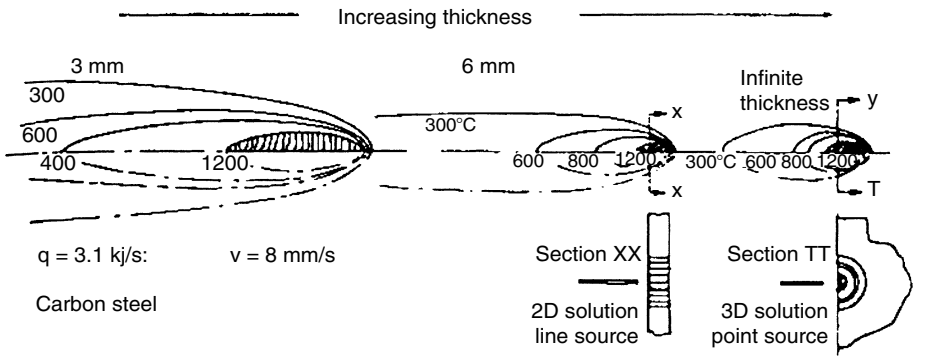

Figure 9.10 Schematic of the effect of weldment (joint) thickness on the weld pool and HAZ size and shape. (Reprinted from *Rational Welding Design*, T.G.F. Gray and J. Spence, Newnes-Butterworth, London, England, 1975, with permission from Elsevier Science, Burlington, MA.)

the effect on weld pool size and shape caused by changes in material (i.e., thermal–physical properties), welding speed, and plate thickness, respectively.

Very briefly, higher thermal conductivity in a base material tends to cause the molten region to be smaller than with lower conductivity; and the surrounding isotherms spread farther and with a less elongated shape, all because heat flows faster from the point of its deposition. Higher welding speeds cause the weld pool and surrounding isotherms to elongate from a circle (for a stationary weld) to more and more pronounced ellipses and, at some point, to a "teardrop" shape. Thicker material causes weld pools to become smaller (as there is more "heat sink" for heat to spread into from the point of its deposition). Convection arising from gravity or buoyancy and a Lorentz force (both of which cause the hotter molten metal in the center of the pool to circulate upward and turn outward to then be forced downward at the pool's edges) tends to spread the pool out and make it less deep. Convection arising from a surface tension gradient or impingement force (both of which cause the hotter molten metal in the pool to circulate from each edge to its center and downward) tends to make the pool deeper and narrower, sometimes causing a protrusion at the bottom of the weld due to concentrated erosion of the base material by superheat molten metal. All of these effects change the severity of the temperature gradients that prevail in the pool and also affect the competitive growth among solidifying dendrites emanating at the pool's sides transverse to the welding direction. This, in turn, affects the mechanical properties of the weld.

9.3.4 Key Principles of Weld, Braze, and Solder Solidification

Entire book chapters (and books!) on the physical metallurgy of welding have been dedicated to fully describing and explaining the mechanism of solidification in welds (and their close cousins, braze and solder joints)—see the bibliography at the end of this chapter. What will be covered in this subsection is the key principles of solidification, most of which are common to brazing and soldering as well as to fusion welds. Just to

let the reader know where this is going, here is a list of the key principles, followed by brief paragraphs on each:

- *Solidification is a process involving first nucleation and then growth,* nucleation being driven by supercooling below the equilibrium melting point or liquidus and limited by diffusion.
- *Nucleation occurs much more easily when it has a substrate on which to begin.*
- *Growth of newly nucleated crystals* (or dendrites), no matter whether it occurs with or without the help of a substrate, *is competitive.*
- *Solidification of pure crystalline metals and ceramics involves only the rearrangement of atoms* without long-range order in the melt into long-range ordered solid, crystal arrays. It can occur by two growth modes, one when there is a positive gradient and the other when there is a negative gradient of temperature from the edge of the weld pool into the pool.
- *Solidification of alloys requires adjustment of the composition between the liquid and solid in contact (or solute redistribution) as well as atomic rearrangement* into a long-range ordered array. It can occur by additional growth modes (compared to pure materials) controlled by the degree to which the liquid ahead of the advancing solid–liquid interface is supercooled relative to the liquidus temperature for the liquid near the interface that is enriched by solute being rejected from the newly forming solid.
- *Understanding of the solidification mechanics of welds is essential to understanding the desired properties of the resulting welds, as well as the origin of unwanted defects in welds.*

So, with this as a "map," let us proceed!

Homogeneous Versus Heterogeneous Nucleation. For a crystalline solid to form from a liquid, atoms lacking any long-range order in the liquid have to come together, by chance, to form an array that has long-range order.[9] The driving force for this to occur is thermodynamics, specifically the reduction of the Gibbs volume free energy of the liquid phase by becoming a solid phase, such that $\Delta G_{vol} = G_{Solid} - G_{Liquid}$ is negative. From the Gibbs volume free energy curves versus temperature for the liquid and crystalline solid phases of a pure metal (for example, in Figure 9.11), it can be seen that below a certain temperature (where the two curves cross one another, known as the "melting point,") G_{solid} becomes lower than G_{liquid}. That phase is the one that is preferred and thermodynamically stable. While it would seem that the solid phase would form as soon as the temperature dropped below the melting point, this is not the case. Some supercooling is needed to provide the thermodynamic "push," or driving force, for the formation of the new solid phase. The reason is that to create the "nuclei" (or embryos, if one prefers) for the new solid phase, two things occur that compete with one another energetically. First, atoms simply come together and take up the arrangement found in the new crystalline solid, lowering the volume free energy G_{vol} in

[9] *Long-range order* means that one can predict that a particular atom will be at a particular location many atomic distances away, in any direction. Crystalline solids exhibit long-range order, and amorphous solids and liquids do not. Liquids lack long-range order but, particularly near the melting point, tend to exhibit short-range order that is some degree of predictable arrangement over only a few atom distances.

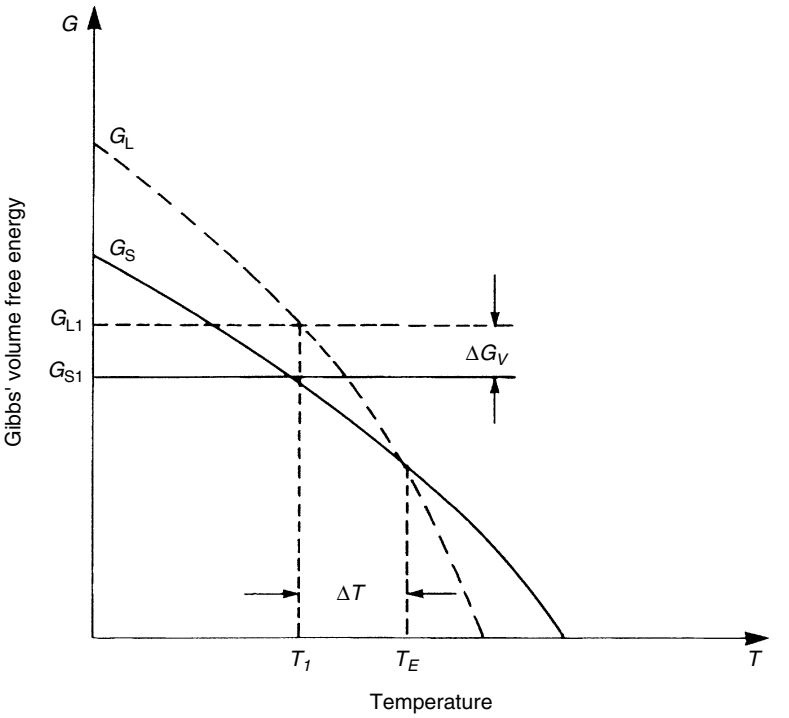

Figure 9.11 Schematic plot of the volume free energy curves as a function of temperature for the liquid and solid phases of a metal showing the net volume free energy change upon solidification. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 7.10, page 252, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

the process. But as soon as this occurs, a new surface is created between the newly formed solid phase and the original liquid phase, and this surface has an energy that is positive. Hence, these two energies compete (as shown in Figure 9.12). The volume free energy, ΔG_{vol}, decreases as r^3 as the nuclei grow (as spheres, with a radius r) to keep their surface-to-volume ratio as low as possible. The surface free energy, γ, increases as r^2 as the nuclei grow. Once the net or total free energy reaches a maximum at r^* (the critical radius), the nuclei become thermodynamically stable and grow spontaneously. This process is known as "homogeneous nucleation."

If a substrate is present that can be wetted (see Subsection 4.3.3, "Adsorption Theory of Adhesion" for an explanation of "wetting"), nucleation can occur more easily as only portions of spherical nuclei with a radius of r^* have to form to be thermodynamically stable. Being portions of spheres rather than full spheres, these nuclei contain fewer atoms, forming more easily by what is always a probabilistic or stochastic process. This is known as "heterogeneous nucleation." Since in fusion welding, brazing, and soldering there is always a solid substrate that must be wetted by the liquid phase for the process to operate, heterogeneous nucleation virtually always occurs in favor of homogeneous

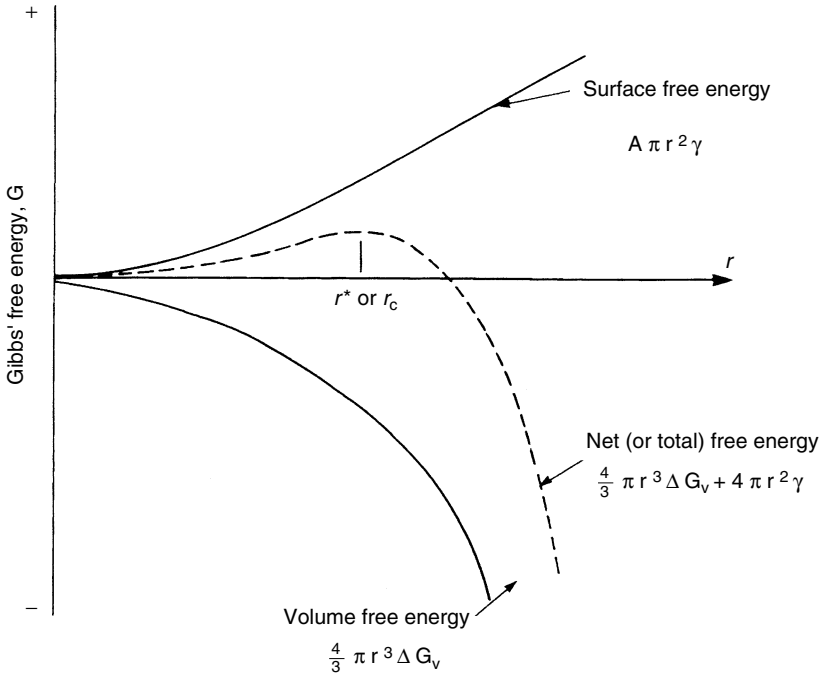
+
Gibbs' free energy, G
−
Surface free energy
A π r 2 γ
r
r* or rc
Net (or total) free energy
4/3 π r 3 Δ Gv + 4 π r 2 γ
Volume free energy
4/3 π r 3 Δ Gv

Figure 9.12 Schematic plot of the total free energy of a pure crystalline metal (or ceramic) during homogeneous nucleation. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Fig. 7.11, page 253, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

nucleation in these processes. In other words, in these processes, welds, braze joints, or solder joints are created on existing material that must (for the process to work at all!) involve compatibility between the solid substrate or base material and molten filler. So, heterogeneous nucleation prevails.

Competitive Growth. When crystalline solids form from liquids, they do so by what is generically referred to as "dendritic growth" (which means "treelike" in Greek). This form of growth results because atoms from the liquid try to add on to the nuclei of the newly forming solid by attaching to them to extend in the closest packed atomic directions for the particular crystal structure. This gives rise to what resembles the stems and branches of a pine tree. In welds as well as in the melt of a braze or solder joint, newly forming solid tries to grow in these "easy-growth" crystallographic directions but, at the same time, grow fastest parallel to the steepest temperature gradient in the liquid. These dendrites also nucleate heterogeneously on the existing unmelted (solid) substrate, extending existing grains in a process known as "epitaxial growth." Thus, newly formed dendrites (that happen probabilistically to have an easy-growth direction established by the grain on which they formed epitaxially that is closely aligned to the maximum temperature gradient in the liquid) grow at the expense of those that are not so favorably aligned. Growth is thus "competitive," with favorably

oriented dendrites growing at the expense of less favorably oriented dendrites. This is shown schematically in Figure 9.13. Competitive growth in fusion welds, brazes, and solders leads to the properties exhibited by the resulting joints.

Pure Crystal Growth Modes. Pure crystalline metals or ceramics solidify by having atoms lacking long-range order in the liquid take up a long-range ordered arrangement in the solid. To do this, all the atoms of the liquid have to do is rearrange to align with the new crystalline structure. While the atoms of the liquid move by a random-walk diffusive process, proper arrangement is facilitated energetically by the formation of bonds. Since growth of a new pure solid phase from a pure liquid can only occur when the temperature in the liquid is below the equilibrium melting point, there are two possibilities under which growth can proceed. The first is when there is a positive gradient of temperature into the liquid. That is, the temperature is lowest at the solid–liquid interface and rises as the distance from that interface increases into the bulk of the liquid. When this is the case, growth proceeds only as fast as the temperature just ahead of the advancing solid–liquid interface drops below the melting point by conduction of heat down the gradient into the solid. The resulting growth mode is called a "planar growth mode." It is characterized by a crystal that grows along a planar front, with atoms from the liquid settling down along the advancing front layer by layer, as a plane. The second possibility is when there is a negative gradient of temperature into the liquid. That is, the temperature is highest and is at the melting point, at the solid–liquid interface and falls progressively farther below that as the distance from the interface into the liquid increases. This is hard to imagine but can occur when, for example, heat extraction and cooling from the surface of a weld pool occur more rapidly by radiation and/or convection than it does through the solid-liquid interface by conduction. The resulting growth mode is called a "dendritic growth mode." It is characterized by a crystal that grows very rapidly as a spike, as the stem of a dendrite, with secondary branches forming normal to that stem into the supercooled liquid. These two possibilities are shown in Figure 9.14.

Alloy Growth Modes and Substructure. Solidification in an alloy is much more complicated than in a pure material. The reason is that atoms from the liquid must not only rearrange themselves into the new crystalline arrangement of the solid, but they must also do so while simultaneously adjusting the composition of the solid from that of the liquid. In other words, the right proportions of atoms of the solvent and any and all solutes must be correct in the new solid. This requirement for solute redistribution comes about from the distribution coefficient between the composition of a liquid and of a solid phase in equilibrium, as shown schematically in the hypothetical binary phase diagram in Figure 9.15. Here the distribution coefficient is $k = C_S/C_L$ at a particular temperature on the phase diagram. Recalling Hume-Rothery's rules for substitutional solid solutions[10]

[10] Hume-Rothery's rules for crystalline solid solutions, in which solute atoms substitute into the lattice of the solvent for solvent atoms, state four conditions for solubility, from most to least important: (1) the difference in size between solute and solvent atoms must be small for higher solubility (with less than 8% difference for complete solubility, and over 15% difference leading to insolubility); (2) the electronegativity of the solute and solvent atoms should be close to one another for solubility (as a large difference will lead to compound formation); (3) the valences of solute and solvent atoms should be close to one another for solubility; and (4) in order for there to be complete solubility, the crystal structure of the solute must be the same as the solvent.

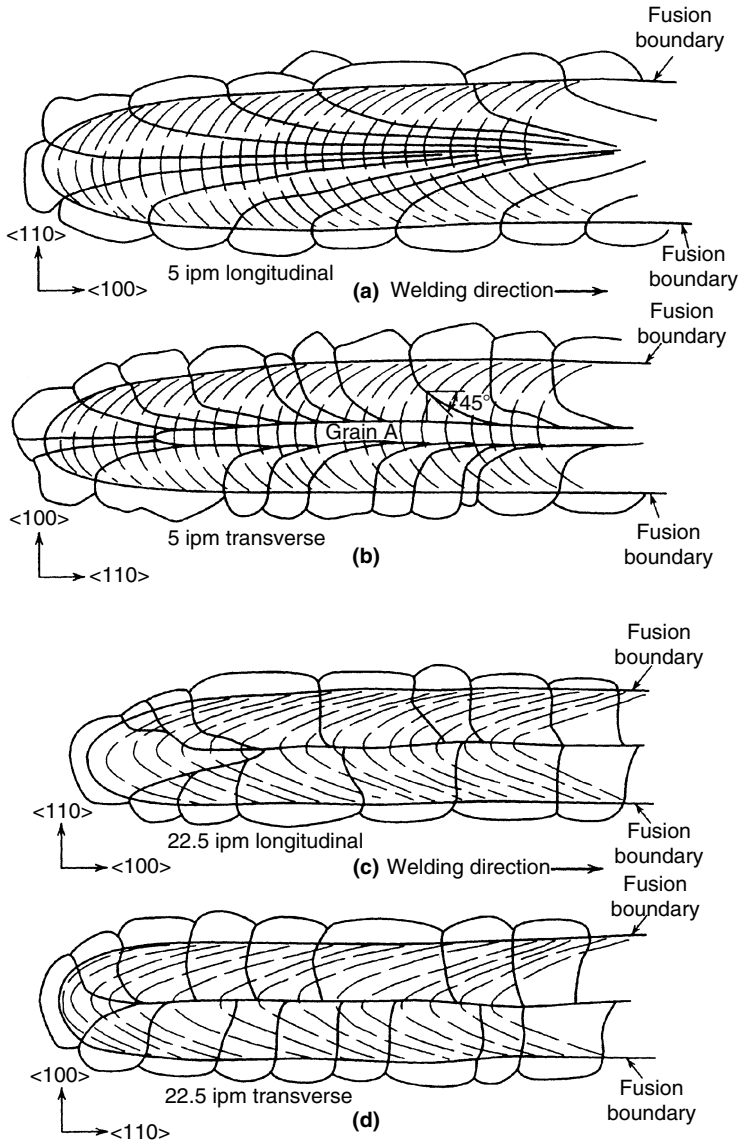

Figure 9.13 Schematic representation of competitive growth occurring in the fusion weld of a typical crystalline metal (or ceramic), showing how epitaxially growing grains for which some easy-growth (crystallographic) direction is closely aligned to the maximum temperature gradient (normal to the weld pool boundary) are favored. Different directions of welding compared to a highly textured silicon iron alloy sheet are shown for a low and a high welding speed. (Reprinted from *Principles of Welding: Processes, Physics, Chemistry & Welding*, Robert W. Messler, Jr., Fig. 13.11, page 397, John Wiley & Sons, Inc., New York, NY, 1999, with permission.)

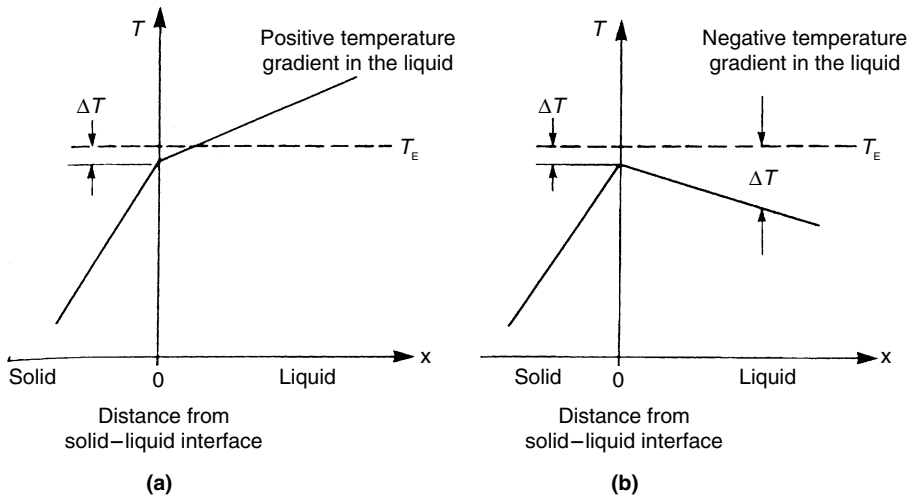

Figure 9.14 Schematic plot showing the two ways by pure crystalline solids can grow (i.e., (a) by a planar growth mode for a positive temperature gradient into the liquid and (b) by a dendritic growth mode for a negative temperature gradient into the liquid). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 7.13, page 255, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

(as found in most alloys), a solid crystal accommodates solute atoms within an array of solvent atoms based mostly on the relative size difference between the two. The greater the difference in solvent and solute atoms' sizes, the fewer solute atoms can be accommodated in the crystal of the solvent. The reason is that size difference equates to lattice strain energy, and the strain energy can get only so high before the crystal will thermodynamically "refuse" any more solute. Thus, the amount of solute tolerated in the newly forming solid is always lower than it is in the liquid where lattice strain energy is not an issue. This requirement for solute redistribution between the liquid and the solid gives rise to additional growth modes in alloys.

Lower solubility of solute atoms in the solvent as a solid than as a liquid (as can be seen on the phase diagram in Figure 9.15) means that for the solid to grow at the expense of the liquid, solute atoms that are not accepted into the crystal lattice are rejected into the liquid ahead of the advancing solid–liquid interface. This leads to a buildup of solute concentration near the interface, which forms a concentration profile like that shown in the upper left of Figure 9.15. This concentration profile, in turn, leads to a corresponding profile of effective liquidus temperature in the liquid ahead of the advancing solid–liquid interface, as shown in the lower left of Figure 9.16. If the actual temperature gradient in the liquid (also shown in the lower left of Figure 9.15) is at or falls below this effective liquidus, the solid phase can grow. Depending on how much below the effective liquidus temperature and how far ahead of the solid–liquid interface the liquid actually supercools, substructures can change from planar to cellular to columnar dendritic to equiaxed dendritic (as shown in the lower left of Figure 9.15). Thus, alloys can solidify with more substructure modes than pure

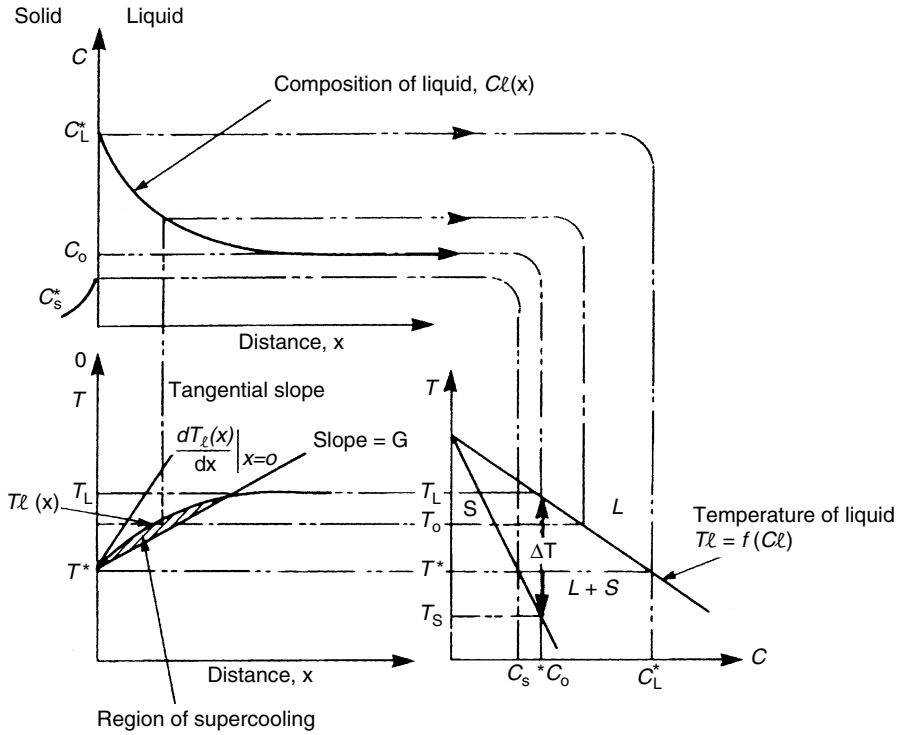

Figure 9.15 Schematic illustration of the origin of "constitutional supercooling" as the driving force for the development of various solidification substructure growth modes in an alloy undergoing non-equilibrium solidification. The development of a solute buildup in the liquid ahead of the advancing solid–liquid interface (in the upper left) arises from the distribution coefficient for solute in solid versus liquid (shown in the phase diagram in the lower right) leading to an effective liquidus that lies above the actual temperature in the liquid (as shown in the lower left). (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 7.16, page 259, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

materials, with different modes having different properties, including yield strength based on scale or coarseness (the finer the better), ductility or toughness, anisotropy, etc.

Figure 9.16 shows how the various possible solid substructure growth modes in alloys relate to the prevailing temperature gradient (G) in the liquid and to the prevailing rate of growth (R), which is inversely related to the solidification time (S_t) (see Subsection 9.2.5), through the ratio of G/R, while the scale (or coarseness or fineness) of the substructure is related to the product of G and R, GR.

Origin of Solidification Defects. The prevailing growth mode in an alloy has a strong influence on the likelihood of the formation of certain types of defects in the newly formed solid of welds, brazed joints, and soldered joints. The most serious—and common—solidification-related defect is the "hot crack." Hot cracks form from the pulling force associated with volumetric shrinkage that almost always accompanies

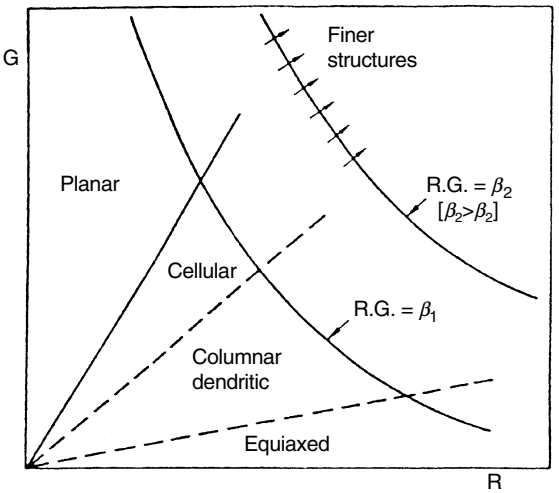

Figure 9.16 Schematic plot of the effect of the prevailing temperature gradient, G, and the rate of growth, R, in the fusion zone of a weld on the solidification substructure mode and scale (i.e., coarseness or fineness). (Reprinted from *New Trends in Materials Processing*, A.F. Gaimei, E.H. Kraft, and F.D. Lemkey, ASM International, Materials Park, OH, 1976, with permission.)

solidification of a liquid into a crystalline solid, aggravated by an additional pulling force from thermal contraction in the surrounding heat-affected zone. If this ever-present tensile pulling force or stress acts on regions of microscopic segregation of low melting, solute-enriched liquid at boundaries between growing dendrites, cracks form. The susceptibility to hot cracking is greater for (1) coarser structures (as there is less grain boundary area over which to distribute low-melting segregate), regardless of growth mode; (2) equiaxed over columnar dendritic, and columnar dendritic over cellular, and cellular over planar substructure growth modes; (3) competitive growth that produces a pronounced centerline along which segregate piles up (as growth proceeds from each side of the weld to the centerline); (4) alloys with larger solidification ranges (i.e., differences between liquidus and solidus temperatures); and (5) alloys with residual or "tramp" elements like S, P, Si, O, and some others.

The key point of all of this is this: the solidification of alloys involves complex mechanics that can lead to the formation of either favorable or unfavorable structures, and it is possible to control the structure by controlling the conditions of welding, brazing, or soldering.

9.4 CONSIDERATIONS IN THE PARTIALLY MELTED ZONE

Just outside the fusion zone of fusion welds (and with no parallel in brazing or soldering, since no melting of the base material is supposed to occur!) is a region that has been heated to a temperature between the liquidus and solidus temperatures

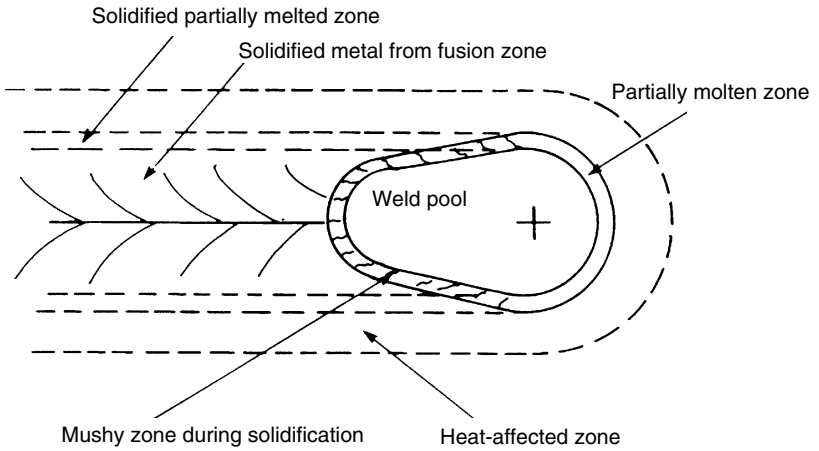

Figure 9.17 Schematic showing the location of the partially melted zone (PMZ) in alloys being fusion welded. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 7.19, page 262, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

for the alloy. In this region the base material is only partially melted; some of it remains solid. This region is called the *partially melted zone* (PMZ). Figure 9.17 shows the location of the PMZ in a fusion weld in a hypothetical alloy. While it is less well understood than the FZ and HAZ (because of the hydro-mechanical complexities of mixed liquid and solid phases), suffice it to say that the PMZ is prone to the formation of hot cracks and some other defects that are far more difficult to control through adjustment of the welding process parameters. The best advice by far is to keep the PMZ as small as possible by limiting the heat input to the weld. But other good practice includes (1) minimizing restraint on the weldment to minimize crack-producing pulling forces; (2) selecting base metals carefully to minimize residual elements; and (3) choosing a filler alloy with a melting point higher than the base metal to force solidification to occur completely in the PMZ before it does in the FZ.

9.5 CONSIDERATIONS IN THE HEAT-AFFECTED ZONE

9.5.1 General Description of the Heat-Affected Zone of Welded, Brazed, or Soldered Joints

The heat of welding (whether sufficient to cause melting or simply to lower the yield strength to facilitate non-fusion welding) can alter the structure in the region immediately adjacent to the weld or braze or solder joint, that is the *heat-affected zone*. This occurs to a lesser extent in brazing, and to a still lesser and often negligible extent in soldering. Whether there is any effect, what effect occurs, and what impact that effect might have on the joint's performance all depend on the mechanism by which the base

material is strengthened. The effect is usually insignificant in "thermally bonded" or welded thermoplastics, because first, heat input and peak temperatures tend to be low and, second, heat on the order needed to produce a weld in such materials rarely causes any degradation. In metals and ceramics (whether pure or alloyed), on the other hand, the effects can be severe.

A complete understanding of welding and the allied processes of brazing, soldering, thermal cutting, and heat straightening demands an understanding of the effects of the process on the heat-affected zone. This section takes a short look at the effects that can be expected in the heat-affected zones of metals and alloys strengthened by one of the following mechanisms: (1) work or strain hardening, (2) solid solution strengthening, (3) precipitation hardening, (4) transformation hardening, and (5) dispersion strengthening. In addition, the effect of heat on the sensitivity of stainless steels is also briefly addressed.

9.5.2 Work-Hardened Metals: Recovery, Recrystallization, and Grain Growth

When a pure metal (commonly W and Mo, and occasionally Al or Cu) or alloy (commonly Cu–Zn brasses, Cu–Be, Cu–Ni cupro-nickels and Monels, and some cold-drawn steels) is plastically deformed or strained below a certain temperature (typically 0.4–0.5 of its absolute melting temperature), existing one-dimensional line imperfections known as "dislocations" are set in motion. Deformation occurs by slip, new dislocations are generated, and these dislocations interact with one another and with obstacles (like precipitates, dispersoids, grain and/or phase boundaries) to form tangles and pile-ups that hinder the further motion of these and other dislocations. This, in turn, restricts further plastic deformation. In this way, the pure metal or alloy is strengthened by cold working, and the mechanism is known as *work hardening* or *strain hardening*.

While only about 5% of the total strain energy put into a metal is stored in the lattice as stretched and compressed bonds (the rest being converted to the work of deformation or heat), this is enough to raise the energy of the system to act as a driving force for recovery. When such a work-hardened metal or alloy is subjected to temperatures over approximately 0.4–0.5 T_{mp} (absolute), the deformed grains tend to nucleate new, strain-free grains in a process known as recrystallization.[11] This actually involves progressive processes to reduce the energy of the system through changes to first point (e.g., vacancies and crowd-ions), then line (e.g., dislocations), and finally area imperfections (e.g., grain boundaries). The steps, which occur in order to whatever extent exposure to elevated temperature and time allow, are known as "recovery,"

[11] In *recrystallization* (like solidification, discussed earlier, and precipitation of a second phase to be discussed next), for a new phase to nucleate, become stable, and grow, the reduction in volume free energy in creating the new phase (free of stored strain energy for recrystallization, just a lower energy structure for precipitation) must offset not only the surface energy of the new interphase interface, but also any strain produced in the surrounding matrix by the new phase's having a greater specific volume.

"recrystallization," and "grain growth." The effect on the microstructure is observable beginning with the recrystallization stage, but the effect on properties begins with the recovery stage. Electrical resistivity (caused by increased scattering of electrons by point imperfections) begins to decrease with the onset of recovery, followed by the reduction of yield strength and hardness and the attendant increase in ductility with the onset of recrystallization. Grain growth has only modest effects on strength, ductility, and toughness beyond recrystallization. These property effects, as well as a schematic representation of the microstructural effects, are shown in Figure 9.18. It is these property effects in the HAZ of cold-worked metals or alloys that have to be taken into account by adjustment of design allowables. They can be circumvented or minimized by minimizing the heat of welding through selection of a high energy density or very fast heating process or by parameter control, or both, or restored by post-weld cold work such as peening, stretching, or roll planishing.

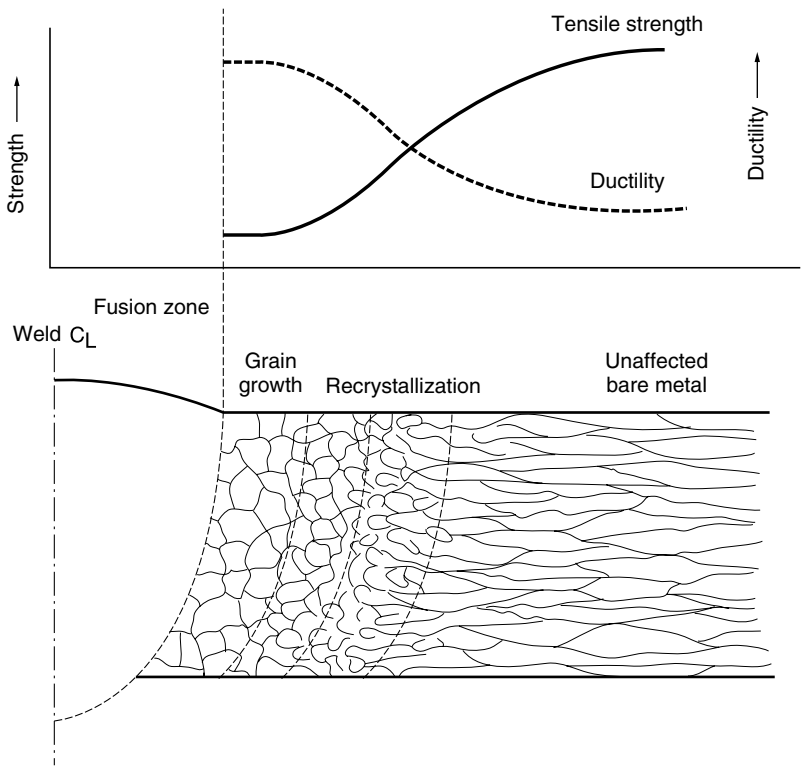

Figure 9.18 Schematic illustration of the effect of the heat of welding, brazing, or soldering on the properties (top) and microstructure (bottom) of a work-hardened metal.

9.5.3 Precipitation-Hardened Alloys: Reversion and Overaging

Certain alloys (such as Al with Cu, Mg + Si, Mg + Zn, or Li, Ni with Al and Ti, or certain "PH" stainless steels and maraging ultra-high-strength steels with Cu and other additions) can be strengthened beyond the effect of solute elements going into solid solution, through the precipitation of a second phase from a supersaturated solid solution produced by heat treatment. For such supersaturation and then precipitation (known as "aging") to occur, the active solute must exhibit limited solid-solubility that decreases with decreasing temperature. To cause the precipitation hardening, the normally two-phase alloy at room temperature (such as that shown in Figure 9.19) must be heated above its solvus temperature into a single-phase solid solution region, then quenched rapidly to room temperature (usually using a water immersion or spray quench) to trap the solute in solution, leading to metastable supersaturation. By next heating this solution-treated alloy to above room temperature but below the solvus temperature, the solute is able to diffuse much more rapidly to allow the solute-rich second phase to precipitate by nucleation and growth. As long as the lattice parameters of the precipitate phase and the parent, matrix phase are close but different, the precipitate tries to remain "coherent" with the matrix, by having bonds between

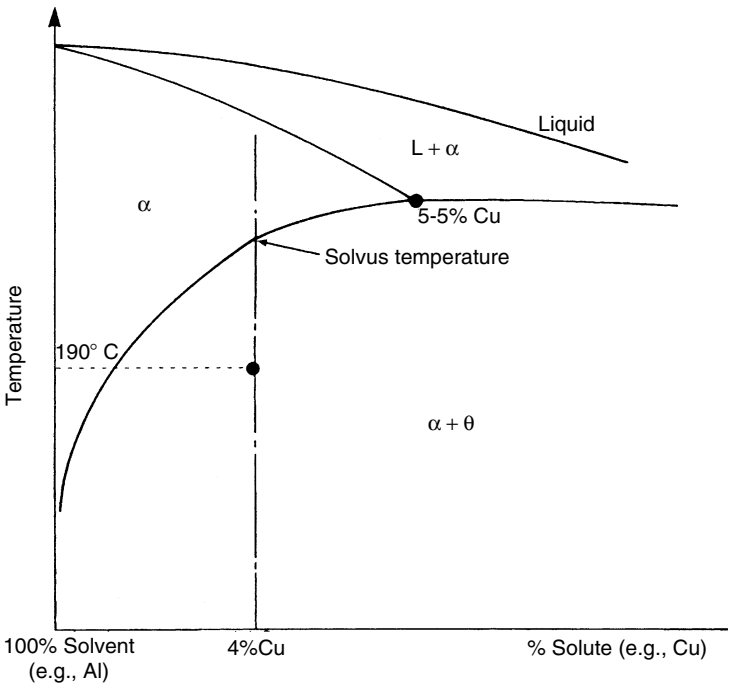

Figure 9.19 Schematic representation of the phase diagram from a binary alloy, B in A, in which precipitation strengthening can occur. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 7.21, page 266, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

atoms in the two phases stretch or compress to accommodate the lattice mismatch. The resulting elastic strain hinders dislocation motion, thus yielding by slip, through repulsion between like components of the strain fields of the dislocations and the coherent precipitate interfaces.

The heat of welding causes two effects in the HAZ of such age-hardened alloys. Nearest the FZ, in the HAZ lying between the solidus and the solvus temperatures, precipitate goes back into solution in a process called "reversion." Outside of this, in the HAZ lying below the solvus but enough above room temperature to allow the solute to have a high enough diffusion rate to cause growth of the precipitate in reasonable times, the precipitates grow to such a size that they lose coherency with the matrix. This drastically reduces their strengthening effect, in a process known as "overaging." The effect in both regions is loss of strength.

These property effects, as well as a schematic representation of the microstructural effects, are shown in Figure 9.20. It is these property effects in the HAZ of precipitation-hardened alloys that have to be taken into account by adjustment of design allowables. These effects can be circumvented or minimized by minimizing the heat of welding through selection of a high energy density or very fast heating process, or by parameter control, or both. An additional method is to weld the alloy in the solution-treated condition and then age the weldment or brazement. This might be acceptable because the temperature for aging is considerably lower than the temperature for solutionizing, so it will tend to create less distortion.

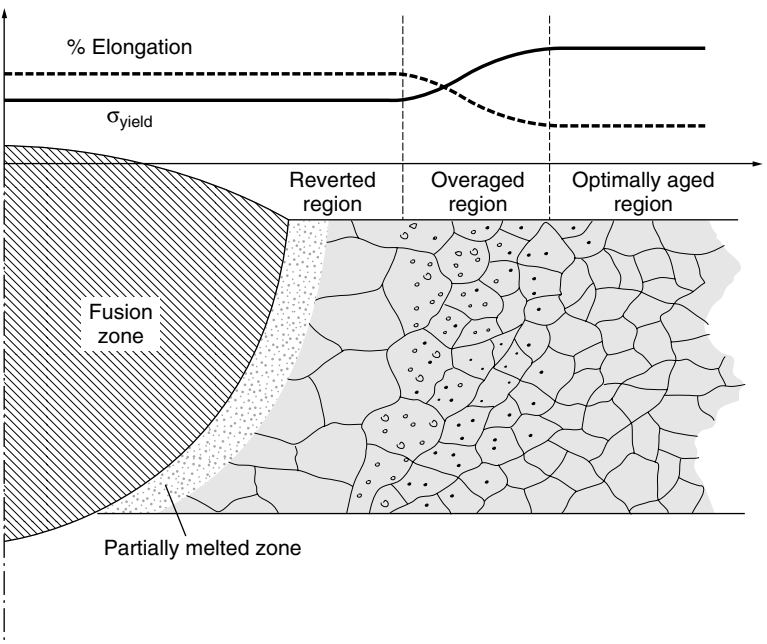

Figure 9.20 Schematic illustration of the effect of the heat of welding, brazing, or soldering on the properties (top) and microstructure (bottom) of an age-hardened precipitation-hardenable alloy.

9.5.4 Transformation-Hardenable Alloys: Hardenability

There are a few alloys that undergo a rather dramatic massive transformation upon rapid cooling at a rate exceeding some critical cooling rate, in what is known as a "martensitic transformation." This most notably occurs in Fe–C alloys (mild steels and cast irons) and Fe–C–X alloys (low alloy steels, where X can be Cr, Ni, Mo, V, or a few other elements). Such ferrous martensites are extremely strong but brittle due to the tremendous strain created in the lattice of the Fe by C that is trapped in undesirable interstitial sites, as the Fe–C solid solution tries to transform from its face-centered cubic, elevated temperature austenite phase to the equilibrium body-centered cubic, ferrite phase at room temperature. When cooling occurs so quickly that the C atoms are not able to diffuse to their preferred interstitial sites in the bcc structure, the lattice is distorted to a body-centered tetragonal form (i.e., martensite). To take advantage of the high strength and lessen the loss of ductility and toughness, as-quenched martensite (known as "untempered martensite") is "tempered" by having its temperature raised above room temperature but well below the austenitizing temperature to allow some of the C to realign to more favorable sites, and reduce lattice strain.

The heat of welding can have either of two effects in the HAZ (and FZ) of such alloys. First, if the alloy is initially in a ferritic–pearlitic (or even bainitic) form, heating above the critical temperatures (i.e., A_1 or $A_{1,\ 3}$, and A_3 or A_{cm}, depending on whether the C content is below or above the 0.8% eutectoid composition, respectively) could result in brittle, untempered martensite formation. On the other hand, if the alloy was initially in a quenched and tempered form consisting of tempered martensite, heating above the A_1, A_1, A_3, or A_{cm} temperatures would produce austenite that might then cool to form untempered martensite (if the cooling rate exceeded the critical cooling rate for the alloy). Or it might cool too slowly to reform martensite. In the first case, intolerable embrittlement might result. In the latter case, unacceptably low strength and hardness might result. In addition, heating the tempered martensite above its tempering temperature in the HAZ could cause overtempering and loss of needed strength.

These property effects, as well as a schematic representation of the microstructural effects, are shown in Figure 9.21. It is these property effects in the HAZ of transformation-hardenable alloys that have to be taken into account by adjustment of design allowables. These effects can be circumvented or minimized by minimizing the heat of welding through selection of a high energy density or very fast heating process or by parameter control, or both. Other methods would be to slow the cooling rate following welding by preheating to prevent unwanted martensite formation, to force-cool if martensite is wanted, or to temper any untempered martensite.

9.5.5 Sensitization in Corrosion-Resistant Stainless Steels

In steels with high but suitably balanced Cr and Ni contents, the Cr (in particular) and the Ni impart corrosion resistance, rendering the steel "stainless" (impervious to

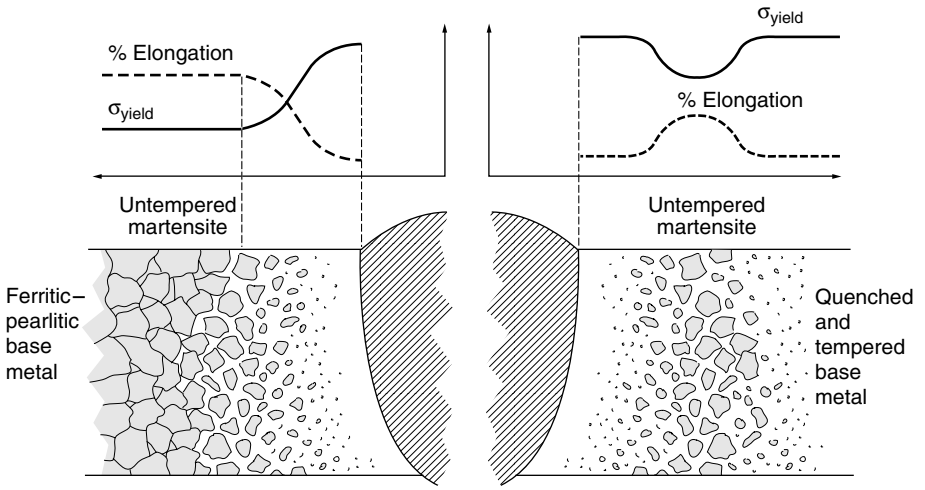

Figure 9.21 Schematic illustration of the effects of the heat of welding or brazing on the properties (top) and microstructure (bottom) of a transformation-hardenable alloy (e.g., a medium carbon steel).

rusting). By appropriate mixes of the ferrite-stabilizing bcc Cr and fcc austenite stabilizing fcc Ni, the resulting stainless steel can be made to be austenitic, ferritic, mixed austenitic–ferritic (i.e., "duplex"), or martensitic (by heat treatment) at room temperature. In the austenitic and ferritic types, C is present in small concentrations (typically less than 0.1 wt.%), at which levels it still provides potent interstitial solid solution strengthening to the Fe–Cr–Ni matrix phase. However, under the heat of welding (as well as elevated temperature exposure in service or heat treatment), the formation of Cr-carbides is promoted. These preferentially precipitate at grain boundaries where diffusion rates are higher for both C and Cr, and where any lattice strain from the carbides can be shared with the grain boundary. When they do, they deplete the Cr content in the matrix phase in the vicinity of the grain boundary. This results in the grain boundary's being less resistant to corrosion than the bulk of the grains, leading to what is known as "sensitization" and "weld decay." The weld decay is the result of grain boundaries in that region of the HAZ where the temperature was high enough to cause Cr-carbide formation (typically about 600–850°C (1,100–1,550°F), known as the "sensitization range") being attacked intergranularly. This leads to loss of integrity of the structure.

This effect on corrosion resistance, as well as a schematic representation of the microstructural effects, is shown in Figure 9.22. This effect in the HAZ of susceptible austenitic and ferritic stainless steels has to be circumvented or minimized (by minimizing the heat of welding through selection of a high energy density or very fast heating process or by parameter control, or both; by lowering the C content to below about 0.03 wt.%, possibly adding back N to offset the loss of strength; or by selecting so-called "stabilized" grades with small Ti or Nb additions to form Ti-carbides or

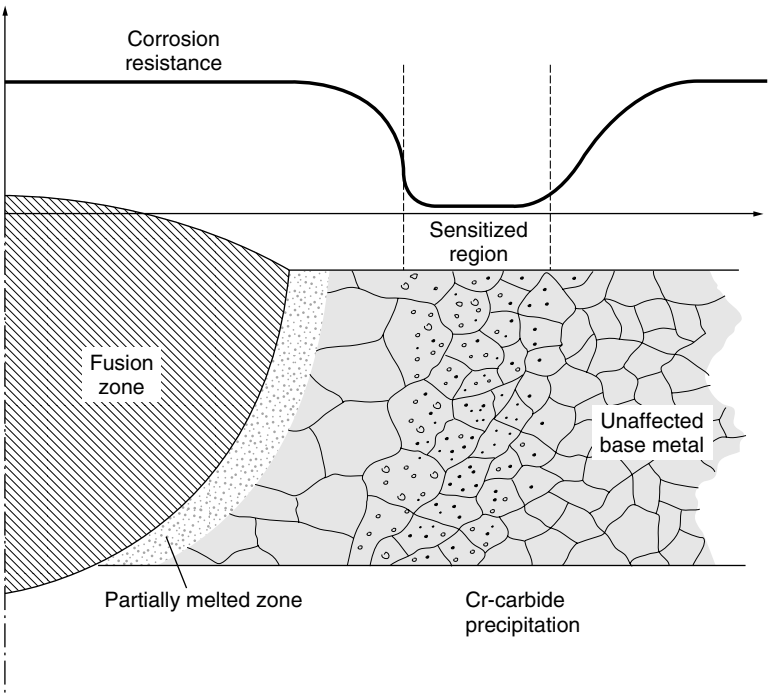

Figure 9.22 Schematic illustration showing effects of the heat of welding or brazing on the relative corrosion resistance (top) and microstructure (bottom) of an austenitic or ferritic stainless steel prone to sensitization and weld decay.

Nb-carbides preferentially to Cr-carbides), or restored (by appropriate post-weld re-solutionization heat treatment).

9.5.6 Solid-Solution Strengthened and Dispersion-Strengthened Metals

The heat of welding really has no effect on single-phase solid-solution strengthened alloys (e.g., Cu–Ni alloys, non–heat treatable Al or Mg alloys, alpha-Ti alloys, and others) or on pure metals (e.g., Al_2O_3-strengthened Al or ThO_2-strengthened Ni) or alloys (e.g., oxide dispersion-strengthened Fe- and Ni-based super-alloys) strengthened with the addition of an inert, thermally stable dispersed-phase. The only effect in solid-solution strengthened alloys might be grain growth, which could lower ductility more than strength. Even this would not occur in dispersion-strengthened metals or alloys, because one of the purposes of the dispersoid is to pin grain boundaries to prevent sliding as a mechanism for elevated temperature creep, and, at the same time, limit grain growth.

Figure 9.23 schematically illustrates typical hardness traverses across welds made in metals and alloys strengthened by various means.

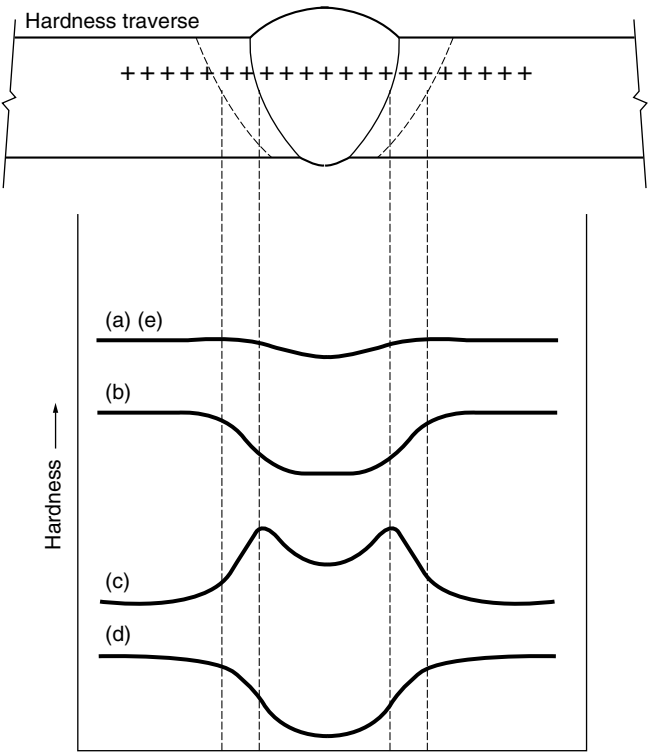

Figure 9.23 Schematic of the typical hardness traverses across a single-pass fusion weld made in metals or alloys strengthened by (a) solid solution alloying, (b) precipitation hardening, (c) transformation hardening, (d) work hardening, and (e) dispersion strengthening.

9.6 DEFECT FORMATION AND PREVENTION IN WELDED, BRAZED, AND SOLDERED JOINTS

9.6.1 General Description of the Origin and Impact of Defects in Joints

The mechanical integrity of a welded, brazed, or soldered joint can be severely compromised by the presence of defects, as such defects almost always act as points of stress concentration. They often reduce the cross-sectional load bearing area and sometimes also degrade the material's properties (especially ductility and toughness). Defects can arise from one or more of several sources, including (1) improper joint design, preparation, or fitup; (2) inherent base or filler material characteristics; (3) process characteristics, or malfunctions; and (4) environmental factors. Defects from these sources can appear in the former melted zone of fusion welds, braze joints, or solder joints, at the interface of non-fusion welds, in the partially melted zone of fusion welds, in the heat-affected zone, or in any combination of these.

9.6.2 Joint-Induced Defects

Improper or inappropriate joint design or preparation or joint element fitup (i.e., misalignment, gaps) can lead to the following types of defects: (1) lack of complete penetration (from improper design or inappropriate process selection, parameter selection, or process malfunction); (2) mismatch or surface offset (from joint element misalignment or heat-induced distortion); (3) severe distortion (from unbalanced thermal masses or excessive heat input); (4) porosity (from entrapped air or contaminant outgassing) or massive voids (from entrapped air, failure of braze or solder fillers to wet, or molten melt or weld-pool dropout of joints that open at their root due to shrinkage stresses); (5) shrinkage voids or cracks (from poor joint element fit or excessive restraint); (6) underfill (from poor fitup); (7) missed seams or cold shuts (from misaligned beams for beam-welding processes or insufficient cleaning or pressure in non-fusion processes); and (8) excessive dilution (from improper joint groove design, process selection, or filler selection for brazing or soldering).

Figure 9.24 schematically illustrates some of the more common joint- or weldment-induced defects found in welded, brazed, or soldered joints.

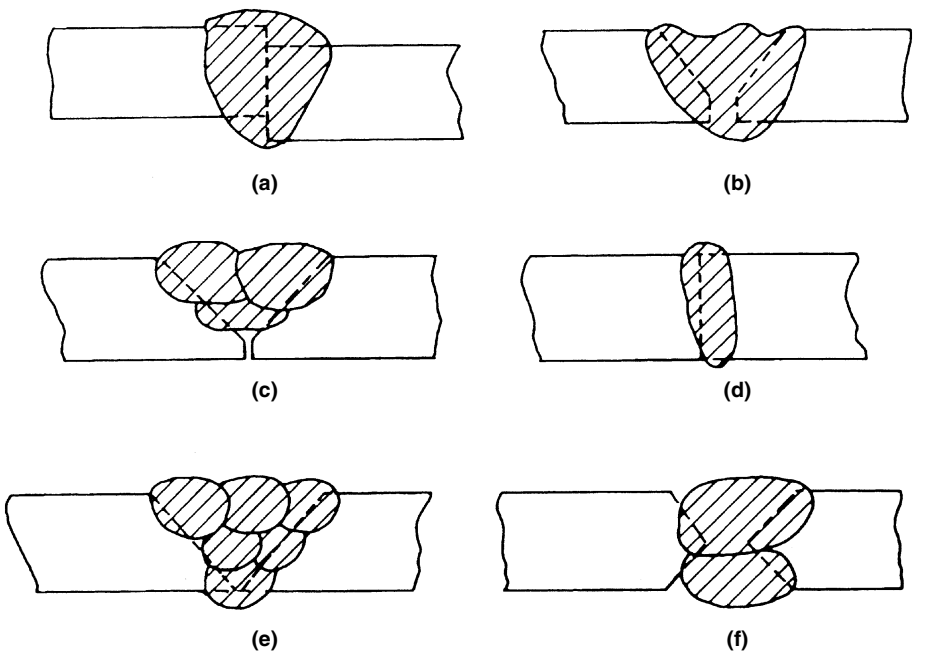

Figure 9.24 Schematic illustration of common joint-induced defects in fusion-welded joints, including (a) misaligned joint elements (or mismatch), (b) underfill, (c) lack of penetration, (d) missed seam (common to narrow laser- or electron-beam welds), (e) lack of fusion in a multipass weld, and (f) undercut at the crown or root of a weld.

9.6.3 Fusion or Melt Zone Defects

One potential defect exclusive to the fusion zone is porosity, which can occur in fusion welds or brazed or soldered joints of any size or configuration. As discussed in Subsection 9.3.2, porosity typically arises from the evolution of entrapped or dissolved gases during solidification of the melt. These gases can come from improper joint preparation (e.g., poor cleaning and the subsequent decomposition of oxides or dissociation of water or hydrocarbon contaminants), the environment (e.g., oxygen, nitrogen or hydrogen from water in the atmosphere or shielding gas, from water dissolved in the coatings or flux-cores of certain consumables, or from hydroscopic fluxes used in brazing or soldering), or the base material (e.g., tramp or residual elements).

The other major source of defects in the fusion zone of welds or the former molten filler in brazing and soldering is *solidification cracking*, also called *hot cracking*. Such cracking is intergranular, occurring along grain or substructure boundaries as the result of microsegregation or exceeding the equicohesive temperature.[12] This form of cracking occurs at the terminal stages of solidification, when the stresses arising from volumetric shrinkage and thermal contraction and acting across the newly formed solid exceed the strength of the almost completely solidified material. The severity of hot cracking increases with both increasing degree of restraint in a weldment, brazement, or soldered assembly (due to fixturing or surrounding structure and mass) and increasing total heat input.

The predominant theory of solidification cracking is that a coherent interlocking solid network separated by essentially thin liquid films is ruptured by contraction stresses. Factors that influence solidification cracking include (1) the freezing temperature range (i.e., liquidus to solidus) for the alloy; (2) the presence of low-melting segregates (from tramp elements); (3) the substructure (growth mode) found in the fusion zone; (4) the nature of any grain boundary liquids (i.e., their surface tension and wetting ability); (5) the magnitude of contraction stresses; and (6) the degree of restraint imposed on the newly solidified joint from all sources. The wider the range between the liquidus and solidus of a weld or braze or solder filler alloy, the greater the cracking tendency. This is because a wider range allows thermal contraction stresses to build to higher levels than narrower ranges, causing tearing of incompletely solidified networks. Alloying elements or impurities like Cu, Mg, or Zn in Al alloys; S, P, or Si in steels; or S or O in Ni alloys aggravate the situation. Related to the width of the freezing range is the final temperature of solidification, with this temperature actually being depressed a hundred degrees C or more in steels, for example, due to non-equilibruim solidification effects. Certain residual elements segregate by solute redistribution and form low-melting compounds (e.g., FeS and Fe_3P in steels) in grain and substructure boundaries that can further tear under contraction stresses well below the equilibrium solidus temperature.

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[12] The *equicohesive temperature* is that temperature above which the grain boundaries become weaker than the bulk structure of the grain.

As always in materials, the structure present in the fusion (or former melted) zone strongly affects the tendency to hot crack. Coarse structures (such as columnar dendrites) are more prone to cracking than fine structures (such as cellular dendrites or cells), because in finer structures the effects of segregates are more spread out, possibly lowering the concentration to below critical levels. Related to this structural effect is the distribution of any liquid present in the grain or subgrain boundaries. Liquids that wet the grains (i.e., have lower surface tensions) promote cracking through the formation of a permeating film, as opposed to more benign localized globules or pockets.

Obviously, hot tearing or cracking cannot occur unless a tensile stress is present. Tensile stresses arise during contraction upon cooling and are aggravated by high thermal coefficients, large volume shrinkages upon solidification, and excessive heat input (which causes the heat-affected zone to be wider). The more restrained a weld or brazed or soldered joint, the higher the stresses that develop during solidification and the greater the likelihood of cracking.

9.6.4 Partially Melted Zone Defects

Hot cracking is the most serious problem associated with PMZs (which are unique to fusion welds) and, like solidification cracking in FZs, is intergranular. The cause of hot cracking in the PMZ is the combination of grain boundary liquation (melting), caused by diffusion gradient effects from carbides of other second-phase compounds during non-equilibrium heating, and stresses induced by both solidification shrinkage and thermal contraction during welding. So-called ''cold cracking'' from hydrogen embrittlement of martensite formed in the PMZ can also occur, especially as the result of backfilling of incipient cracks by solute-rich (and thus very hardenable) liquid.

The location of cracks in a weld fusion or partially-melted zone tells a lot about their source. Figure 9.25 schematically illustrates some defects commonly associated with the FZ (or melt zone) and PMZ.

The closest equivalent to PMZ cracking in fusion welds found with brazing or soldering is cracks in a brittle intermetallic layer almost always found with braze and, particularly, solder fillers. This intermetallic layer is formed as a result of interdiffusion of one or more components in the molten braze filler or solder into the solid substrate to react with one or more of the components of the base metal. Formation of such compounds by braze fillers is most often associated with reactive brazed fillers containing Ti or Zr, as both elements readily form compounds with other metals (all of which are brittle because of their ordered structure). For solder alloys, Sn and In (the two most extensively used solvents for solders) are notorious for forming brittle intermetallic compounds with many metals, including Cu, for which soldering is particularly widely used in electronic assembly and microelectronic interconnects. The mechanism of cracking can be simple thermally induced stress cracks (which are transgranular) but can be thermomechanically induced fatigue cracks (which are also transgranular). In either case, these cracks tend to run along the filler alloy–base metal interface, just inside the intermetallic layer on the base metal side. (This is obviously analogous to the ''weak boundary layer'' found with many adhesive-bonded joints.)

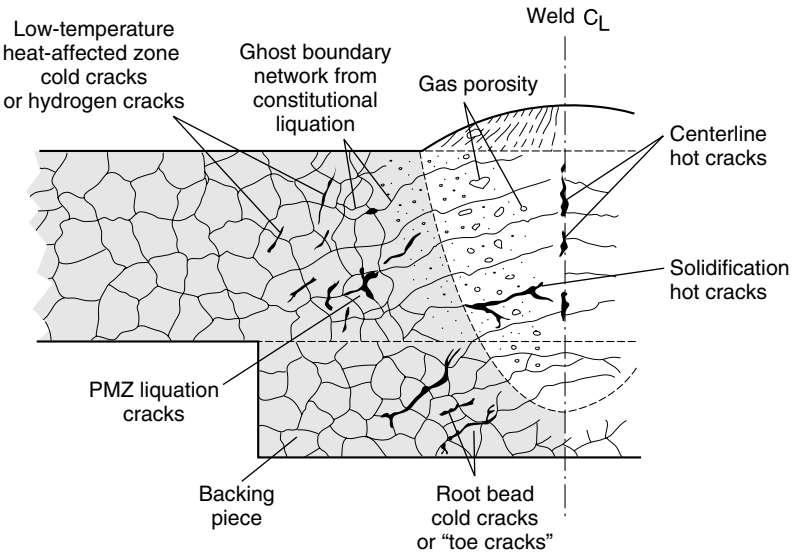

Weld C_L
Low-temperature heat-affected zone cold cracks or hydrogen cracks
Ghost boundary network from constitutional liquation
Gas porosity
Centerline hot cracks
Solidification hot cracks
PMZ liquation cracks
Backing piece
Root bead cold cracks or "toe cracks"

Figure 9.25 Schematic illustration of common fusion zone and partially melted zone defects in fusion welds.

9.6.5 Heat-Affected Zone Defects

Defects in the heat-affected zone of welded, brazed, or soldered joints must develop in the solid state (i.e., without melting) and usually involve thermally induced stresses, often combined with embrittling phases. Three predominant types of defects are found in HAZs: (1) ''hydrogen cracks'' or ''cold cracks,'' (2) ''reheat cracks,'' and (3) ''lamellar tearing.'' *Hydrogen cracking* requires four factors to be present simultaneously: (1) hydrogen must be introduced into or be present in the weld metal, braze filler, solder, or base metal to diffuse into the HAZ; (2) high tensile stresses must be present to attempt to pull open the structure; (3) a susceptible microstructure (such as martensite in steels, but also some ordered intermetallic compounds, such as titanium and iron aluminides) must be present; and (4) relatively low temperatures (-100–$200^\circ C$ (-150–$400^\circ F$)) must usually prevail. The actual formation of cracks can take time, mostly because hydrogen must diffuse to the eventual crack site to nucleate the crack. The fact that cracking occurs at relatively low temperatures leads to the other common name for hydrogen cracking (i.e., ''cold cracking''), while the fact that time may pass before cracks appear leads to the name ''delayed cracking.''

Sources of hydrogen were described in Subsection 9.3.2, but the most prevalent sources are water or moisture on parts, in the air, in shielding gases (or the hoses or lines carrying the shielding gases), or in fluxes (on, in, or used with fillers), hydrated oxide or tarnish layers, and hydrocarbon contaminants (e.g., oil, grease, paint, etc.). High tensile stresses can be induced by high heat input (which gives rise to extensive shrinkage), steep temperature gradients, and/or restraints on the joint. The restraints

can come from tooling or fixturing that is purposely used to align and hold in place parts of the assembly to be joined, or the inherent rigidity of the surrounding structure. A susceptible microstructure, like untempered martensite in steels, can arise from rapid cooling after welding (often, simply from the cool thermal mass surrounding the locally very hot joint).

The exact mechanism of hydrogen cracking has long been the subject of debate, with two competing theories still prevailing: (1) the reduction of cohesive strength of the lattice of certain materials (microstructures), in the Troiano theory, and (2) reduced surface energy of any crack that forms (making crack growth to reduce strain energy less energetically expensive), in the Petch theory. High hydrostatic pressure developed in the crack, at the crack tip, is often considered a contributing factor as well.

Hydrogen cracking can be prevented by eliminating any of the first three factors giving rise to it: removing any and all sources of hydrogen; minimizing the development (or service application) of tensile stresses; or avoiding the use or formation of susceptible microstructures. Eliminating hydrogen is accomplished by proper attention mostly to cleanliness, but also to proper selection and storage of coated SMAW electrodes, cored FCAW wires, or fluxes for SAW, brazing, or soldering. Minimization of tensile stresses is accomplished by minimizing restraint and the creation of thermally induced stresses (mostly by managing the heat of fusion welding). Also, post-process thermal stress relief (to lower or remove residual stresses) as soon as possible is always a good idea. (This also serves to "bake out" any hydrogen from some, but not all, metals.) Avoiding the formation of untempered martensite in fusion welding is accomplished by employing preheat to reduce cooling rates to below the critical cooling rate. Another useful technique is to use a filler of lower strength than the base material to help reduce the development of high tensile stresses in the base material by allowing the filler to yield under the thermally induced stresses.

Reheat cracking is typically a problem in corrosion- or heat-resisting alloys, especially ferritic steels with Cr, Mo, or V, age-hardenable (containing Ti/Al) Ni-based alloys, and some of the heat-treatable/age-hardenable Al alloys. The problem is caused by the formation of complex, brittle compounds at grain boundaries in the HAZ within certain temperature ranges. Cracking occurs under the action of shrinkage and cooling-contraction stresses. There are heat-treating procedures that can offset the tendency toward reheat cracking but, once again, limiting heat input to the bare minimum required to produce an acceptable joint is the best tactic.

Lamellar tearing is the result of a combination of high localized stresses due to weld contraction and low ductility of the base metal in its through-the-thickness direction due to the presence of elongated non-metallic inclusions or stringers (often of silicates, occasionally of sulfides). Tearing is triggered by the fracture of these inherently low-strength and brittle inclusions. This is a material problem that should be addressed by proper alloy composition control and processing but can sometimes be overcome by proper joint design to orient aggravating stresses in the direction of the stringers, as opposed to across the stringers.

Table 9.1 summarizes the defects commonly found in weldments and welds, brazements and braze fillers, and solder assemblies and solders.

Table 9.1 Common Defects Found in Welded, Brazed, and Soldered Joints

Mechanical (Joint or Process)	*Metallurgical (Base Material)*	*Environmental (Surroundings)*
Welded Joints		
Misaligned joints	Hot (fusion zone) cracking	Gas porosity
Missed joint/seam	Centerline cracking	Hydrogen (cold) cracking
Lack of penetration	Liquation cracking	Underbead cracking
Melt-through	Strain-age (reheat) cracking	Oxygen embrittlement
Underfill	Sensitization (cracking)	Stress-corrosion cracking
Undercut	Quench cracking	
Incomplete fusion	Lamellar tearing	
Inclusions	Excessive grain growth	
- tungsten		
- slag		
Gas porosity		
Brazed Joints		
Improper wetting	Intermetallic embrittlement	Gas porosity
- voids	Hot (solidification) cracking	Oxygen embrittlement
- lack of fill/flow	Liquation (phase separation)	
Misaligned joints		
Improper gap		
- filler starvation		
- slumping		
Soldered Joints		
Improper wetting	Intermetallic embrittlement	Gas porosity
- voids		Oxygen embrittlement
- lack of fill/flow		
Excessive solder		
Solder starvation		
Solder "bridging"		

9.7 TESTS OF WELDABILITY AND JOINT PROPERTIES

9.7.1 General Discussion of Weldability and Joint Property Tests

The suitability of a material for welding can often be assessed using tests that evaluate the susceptibility of that material to defect formation. Such tests are known as "weldability tests." To be most meaningful and useful, these tests should be representative of the process and the joint design being considered. They principally assess susceptibility to defect formation in specific areas of the weld—some assessing the susceptibility to FZ solidification cracking, some the susceptibility to PMZ cracking, and some the susceptibility to HAZ cracking.

Once it is known what the inherent weldability of a particular base material is for a particular process and joint design, it is also important and useful to know what properties can be expected from the welded joint. These are called "weld property tests."

The subjects of the "brazeability" or "solderability" of materials are covered in Chapter 7 (Subsection 7.5.6) and Chapter 8 (Subsection 8.8.2), respectively, while the subjects of braze joint and solder joint testing are covered in Subsections 7.7.3 and 8.8.3, respectively.

9.7.2 Solidification Cracking Susceptibility Tests

Solidification cracking susceptibility tests assess the propensity of a material and/or a process and joint configuration to hot crack formation in the fusion zone owing to the existence of unfavorable freezing ranges, low melting eutectics, grain boundary films, and excessive thermally induced stresses. Three popular tests are the Houldcroft Test, the Varestraint Test, and the Circular Patch Test. In addition, weld simulators are used, such as the Gleeble.

The Houldcroft Test is used predominantly to assess sheet gauge materials. The specimen (shown in Figure 9.26) is free of external constraints, but a progression of slots of increasing length across the width of the specimen allow the dissipation of stresses internally. If there is a tendency toward hot cracking, cracking starts immediately and progresses to where sufficient stress has been dissipated by the slots that propagation is arrested. The crack length from the starting edge to the point of arrestment is an index of solidification cracking tendency. The Varestraint Test applies an augmented strain to a test specimen by bending it over a controlled radius at an appropriate time during welding. Both the amount of strain applied and the crack length (either total lengths of all cracks or the length of the longest crack) serve as an index of cracking susceptibility. This test is shown schematically in Figure 9.27.

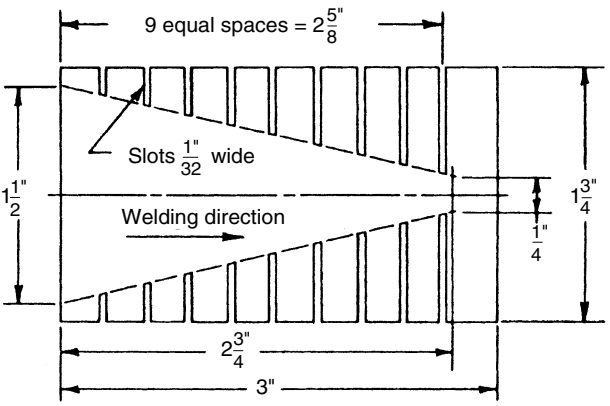


Figure 9.26 Schematic illustration of the Houldcroft Test for FZ hot cracking. (Reprinted from *Welding Evaluation Methods*, J.J. Vagi, R.P. Meister, and M.D. Randall, Defense Metals Information Center (DMIC) Report 244, Columbus, OH, 1968, with permission of the Advanced Materials & Processes Technology Information Analysis Center (AMPTIAC), Rome, NY.)

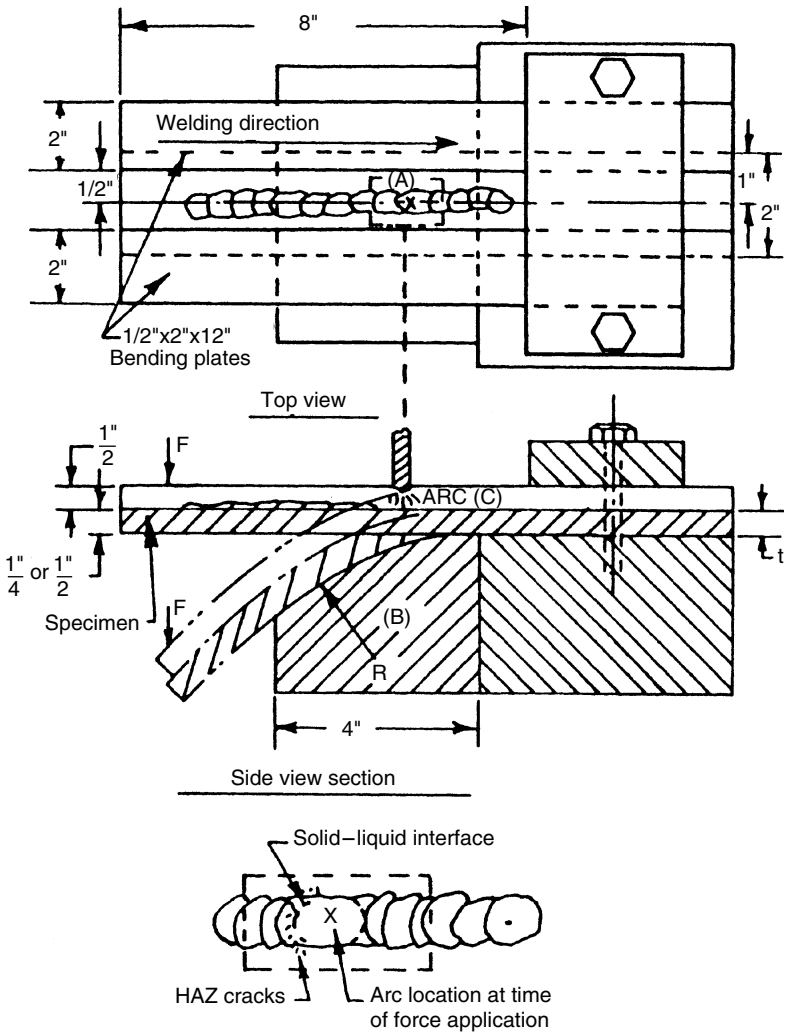


Figure 9.27 Schematic illustration of the Varestraint Test for FZ or PMZ cracking. (Reprinted from *Welding Evaluation Methods*, J.J. Vagi, R.P. Meister, and M.D. Randall, Defense Metals Information Center (DMIC) Report 244, Columbus, OH, 1968, with permission of the Advanced Materials & Processes Technology Information Analysis Center (AMPTIAC), Rome, NY.)

The Circular Patch Test welds progressively smaller diameter plugs, or patches, back into a plate from which they were removed by machining. Cracking, if it is to occur, occurs when the stress from shrinkage exceeds the ability of the material to sustain it.

A much more sophisticated approach for assessing weldability is to use devices that simulate the welding cycle, including temperature and strain as functions of time.

These "weld simulators" actually measure hot ductility of the base metal and/or any filler material. They typically program the thermal cycle produced by a particular welding process and measure the hot ductility of specimens of the base material to be welded over appropriate temperature ranges, on both heating and cooling. One of the most popular weld simulators is the Gleeble. The Gleeble applies either a controlled tensile load or controlled tensile strain (such as the stroke of a ram) to a specimen that is resistance-heated to the temperature range of interest, to assess hot ductility on heating and on cooling. The ability to program the Gleeble's time-temperature load (or stroke) cycle allows specific microstructural regions of welds to be expanded to cover the entire gauge length of the test specimen, reproducing the desired (and questionable) microstructure.

9.7.3 Partially Melted Zone Cracking Susceptibility Tests

The Varestraint, Circular Patch, and Gleeble tests can also be used to assess cracking susceptibility in the PMZ of base materials. When the Varestraint Test is used, the length of cracks only in the PMZ is assessed. In the Circular Patch Test, cracking usually occurs 360 degrees around the outer (as opposed to inner) edge of the weld. In hot ductility tests, such as those of the Gleeble, cracking is assessed in the temperature range between the liquidus and the solidus.

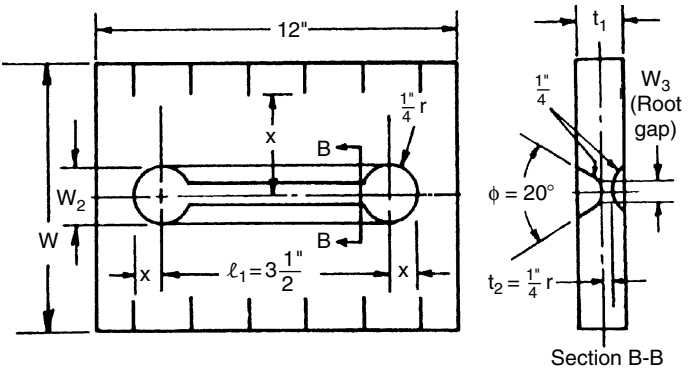
9.7.4 Heat-Affected Zone Cracking Susceptibility Tests

Hydrogen cracking susceptibility is assessed using such tests as the Lehigh Restraint Test, the RPI Varestraint Test, the Lehigh Slot Welding Test, the Implant Test, and the Gleeble weld simulator. Lamellar tearing can be assessed using the Lehigh Cantilever Lamellar Tearing Test, the Cranefield Lamellar Tearing Test, and the Tensile Lamellar Tearing Test. The interested reader is referred to excellent source books on weldability testing, such as those available from the Defense Metals Information Center. Some of these tests are shown schematically in Figure 9.28.

Table 9.2 lists some popular weldability tests and their purposes.

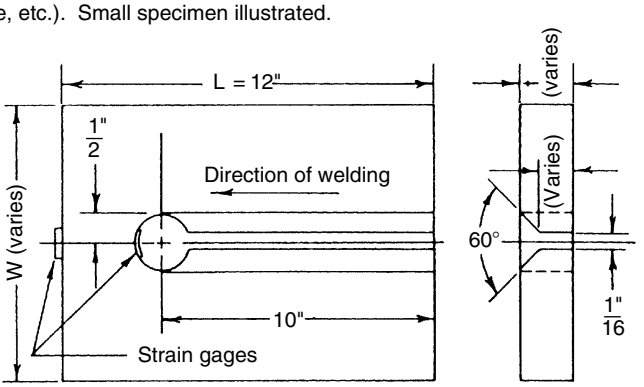
9.7.5 Weld Joint Property Tests

Actual welded joints, brazed joints, or soldered joints can be tested for a host of mechanical properties, as appropriate to the intended application. Static tensile strength, elevated tensile strength, creep stress-rupture behavior, fatigue behavior (i.e., strength and life), impact toughness, fracture toughness, bend ductility, and other more specialized properties (e.g., ballistic impact resistance or explosion-bulge resistance from depth charges used against submarines) can all be tested using specially designed (and standardized) specimens. For the purposes of this book, suffice it to say that any test should replicate actual materials, processes, process parameters and conditions, joint configurations and preparation procedures, and types of loading as



Dimensions, inches									
l_1	L	W	X	W_2	W_3	t_1	t_2	$\phi^{(a)}$	R
3-1/2	12	8	Var.	1/2	1/16	<1	1/4	20°	1/4
5-1/2	12	8	Var.	1/2	1/16	>1	1/4	20°	1/4

Dimension X usually varied in 1/2-inch increments. Temperature of base plate at time of depositing test weld varied depending on condition studied, (i.e., preheat, ambient temperature, etc.). Small specimen illustrated.



Restraint varied by varying L, W, and t; normally L held constant; example—for t = 1/2 inch, W varied from 6 to 10 inches.

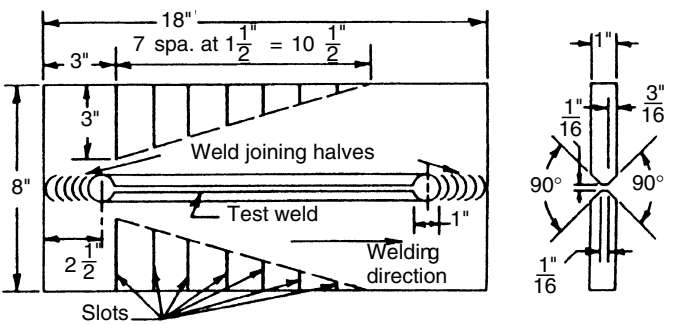
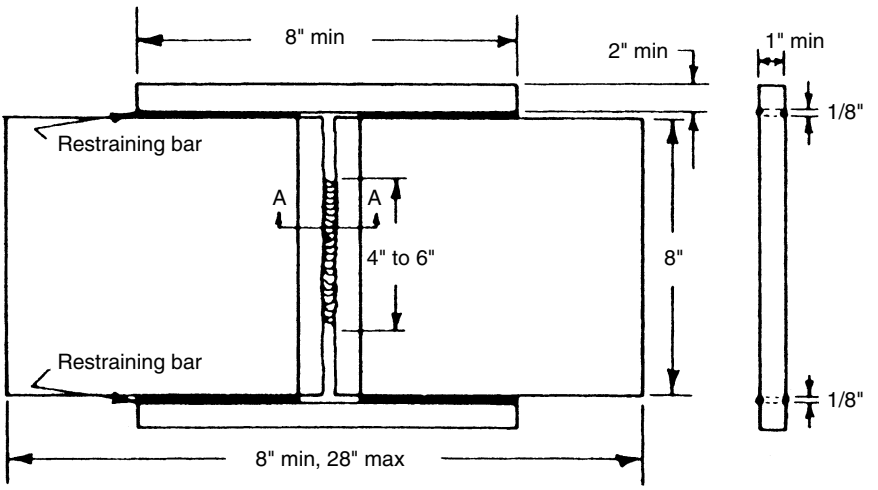
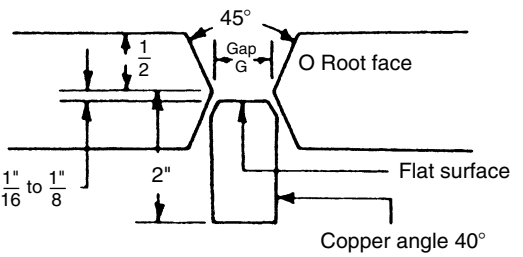


Figure 9.28 Schematic illustration of some popular tests for assessing HAZ weldability: (a) Lehigh restraint-cracking test, (b) keyhole-slotted-plate restraint test, (c) Battelle (crack-susceptibility) test, and





Section A-A

Electrode diameter, in.	Root gap (G), in.	Root-bead thickness, in.
5/32	3/16	0.160 - 0.200
3/16	1/4	0.185 - 0.240
1/4	5/16	0.250 - 0.330
5/16	3/8	0.280 - 0.360

Figure 9.28 (*cont'd*) (d) root-pass crack-susceptibility test. (Reprinted from *Welding Evaluation Methods,* J.J. Vagi, R.P. Meister, and M.D. Randall, Defense Metals Information Center (DMIC) Report 244, Columbus, OH, 1968, with permission of the Advanced Materials & Processes Technology Information Analysis Center (AMPTIAC), Rome, NY.)

Table 9.2 Some Commonly Used Tests for Weldability (Base Metal[1] or Filler[2])

Fusion Zone (Solidification) Cracking Susceptibility	
Battelle test[1,2]	Keyhole slotted plate test[2]
Circular patch test[1,2]	Lehigh restraint test[1,2]
Circular (or segment) groove test[1,2]	Murex test[2]
Cranfield (lamellar tearing) test[1]	Navy circular-fillet weldability (NCFW) test[2]
Finger test[1,2]	Restraint-patch test[2]
Gleeble hot ductility test[1]	Root-pass crack test[2]
Houldcroft test[1]	Varestraint test[1,2]
Heat-Affected Zone Cracking Susceptibility	
BWRA test[1]	Keyhole slotted plate test[2]
Circular patch test[1,2]	Lehigh restraint test[1,2]
Controlled Thermal Severity test[1,2]	Restraint-patch test[2]
Cruciform test[2]	Spiral notch test[1,2]
G-BOP test[2]	Tekken test[1,2]
Gleeble hot ductility test[1]	Varestraint test[1,2]
Implant test[2]	Vinckier test[1,2]

Table 9.3 List of Common Tests Used to Assess Welded Joint Properties*

Base metal tensile tests	Guided bend tests (face, root, edge)
- Longitudinal test	Charpy V-notch impact test
- Transverse test	Plane strain fracture toughness test (ASTM E349)
All-weld-metal test	Drop-weight (impact) test
Transverse weld test	Fatigue tests
Longitudinal weld test	Creep, creep-rupture,
Fillet weld shear test	stress-rupture tests (ASTM E139)
Tension-shear test	Corrosion tests (crevice, pitting, intergranular,
- For brazed joints	stress-corrosion)
- For spot-welded joints	Hardness tests (Brinnell, Rockwell, Vickers, Knoop tests)

*Refer to ANSI/AWS B4.0, *Standard Methods for Mechanical Testing of Welds*

closely as possible. Again, the interested reader is referred to specialized treatments of weld testing listed in the bibliography at the end of this chapter.

Table 9.3 lists the ASTM standards for popular weld joint property tests.

SUMMARY

Fusion welding, brazing, and soldering always involve the application of heat to effect the formation of chemical bonds to produce a sound joint between materials. This is frequently true in non-fusion welding as well. In fusion welding, brazing, and soldering this heat is sufficient to cause melting of the base material (in the case of welding) and the fillers (in the cases of brazing and soldering, as well as in the case of fusion welding

employing filler). Understanding the distribution of the heat once it is deposited in the workpiece by the process heat source, and its effects on (1) the microstructure of the fully melted material(s), (2) any partially melted material in the base material, and (3) the ever-solid heat-affected zone surrounding the melt proper is critical to fully understanding the material science of the highly non-equilibrium processes of melting, solidification, and solid-state phase transformations involved.

Not all of the energy from a thermal joining (i.e., welding, brazing, or soldering) heat source contributes directly to the formation of the weld or, in the cases of brazing and soldering, the melt. Some of the energy is lost in transfer to the workpiece (reflecting the transfer efficiency of the particular process), while that which does arrive at the workpiece is distributed between the fully melted fusion zone (or melt), any partially-melted zone in alloys being fusion-welded, and the surrounding heat-affected zone. Solutions to the general equation of heat flow (often using simplifying assumptions to the degree than these are necessary to ease computation and are reasonable for the real situation, or by fitting experimental data to empirical equations) allow certain predictions: (1) peak temperatures attained at any point, fusion zone and heat-affected zone widths; (2) fusion zone solidification times and rates; and (3) heat-affected zone cooling rates. These, in turn, enable assessment and prediction of weld structure, substructure, and properties.

Within the fusion or molten region, weld, braze, or solder composition is affected by absorbed gases from the environment, leading to porosity, voids, incomplete filling, embrittling inclusions, or embrittlement of susceptible microstructures. It is also affected by metallurgical refinement due to fluxes and their slags, and by dilution of filler by melted base material in fusion welding or by interdiffusion in brazing and soldering. Weld size and shape are affected by the thermal–physical properties of the base material, the process heat source characteristics, process operating mode or other conditions, process parameters (especially speed for moving heat sources), and thickness of the joint.

The process of solidification in pure crystalline materials and alloys is similar in that both require the temperature to fall below the equilibrium melting point (after the melt has been superheated). Both require the dissipation of latent heat evolved during solidification and both depend on the two-step process of nucleation and growth, regardless of whether that nucleation occurs without the aid of a substrate (i.e., in homogeneous nucleation) or with the aid of a substrate (i.e., in heterogeneous nucleation). Growth always occurs competitively by trying to take place in those preferred crystallographic directions that are aligned most closely with the steepest temperature in the joint. In pure materials, a *planar mode* is observed when the temperature gradient in the liquid is positive and a *dendritic mode* is observed when the temperature gradient is negative. Solidification of alloys has the added complexity (beyond simply waiting for atoms in the melt to rearrange themselves to the new, long-range ordered structure of the solid) of having to wait for solute to be redistributed in the solid at a lower concentration than is found in the liquid. Non-equilibrium cooling leads to solute buildup in the liquid ahead of the advancing solid–liquid interface, which leads to what is known as "constitutional supercooling," with the actual temperature in the liquid being below the effective liquidus created by the solute profile prevailing in the liquid ahead of the moving solid–liquid interface. The result of all of this is the occurrence of additional substructure growth modes ranging from planar

through cellular (or cellular dendritic) to columnar dendritic and, finally, to equiaxed dendritic. The first and last are like those found in pure materials. In the new solidification structure of alloys, non-equilibrium also leads to microsegregation that, in turn, leads to hot crack defect formation.

In the HAZ, the heat of welding, brazing, and, to a lesser extent, soldering causes structural changes in different materials, depending on the predominant mechanism of strengthening in those materials. Work-hardened materials soften under the heat of joining due to the progressive steps of recovery, recrystallization, and grain growth in the general process of recrystallization. Age-hardened alloys also soften due to either the total dissolution (i.e., reversion) of the second-phase precipitate in the high-temperature HAZ or simply overaging of the precipitate in the lower temperature HAZ. In alloys hardenable by quenching, either excessive hardening (with loss of ductility and toughness) can occur, or softening of preweld hardened structures can occur by overtempering. In austenitic and ferritic stainless steels, the heat of welding can lead to "sensitization" of grain boundaries to intergranular corrosive attack brought about by the preferential precipitation of grain boundary Cr-carbides (and attendant depletion of Cr in the surrounding matrix). Little or no adverse effects of welding heat are found in single-phase, solid-solution strengthened and dispersion-strengthened metals and alloys. Proper joining by welding, brazing, or soldering requires that these problems be dealt with.

Defects can occur in welded, brazed, or soldered joints because of improper joint design, improper joint preparation, improper process selection or operation, inherent material susceptibility to cold or hot cracking, or other defects, and other sources. Defects can be avoided by knowledge gained from tests of the base material's inherent ability to be welded, brazed, or soldered, using a combination of weldability, brazeability, or solderability tests and weld, braze, or solder joint property tests.

QUESTIONS AND PROBLEMS

1. Using the plot of a typical thermal cycle for a weld made by the SMAW process, superimpose onto this plot the typical thermal cycle one might expect for each of the following processes: (a) oxy-fuel gas welding (e.g., OAW); (b) resistance spot welding (RSW); (c) torch brazing; (d) resistance brazing; and (e) oven soldering.
2. Make a "to-scale" sketch of the microstructural zones one would find in each of the following: (a) pure Al autogenously welded by GTAW; (b) AA3003 autogenously welded by GTAW; (c) AA3003 vacuum-brazed with BAlSi (eutectic); and (d) AA3003 soldered with a Zn–Al eutectic solder.
3. Long (3 m), wide (1 m) sheets of 6.0-mm-thick commercially pure (CP) titanium are autogenously plasma arc welded together with only a straight-butt joint preparation, no groove. The process is operated with DC EN and produces near-parallel-sided welds using a current of 160A, a voltage of 20v, and a welding speed of 200 mm/min. The weldment starts out at 17°C. Calculate and plot the peak temperature reached at distances of 0.5 1.0, 2.0, 4.0, 6.0, 8.0, 10.0, 15.0, 25.0, and 50.0 mm from the fusion zone boundary. Assume a transfer efficiency of 80% (i.e.,

keyhole operating mode). The melting temperature of CP Ti is 1668°C, and key thermal-physical properties are thermal diffusivity (α) = 9.0× $10^{-6}m^2$-s^{-1}, volume-specific heat capacity (ρC) = $3.0 \times 10^6 Jm^{-3^\circ}K^{-1}$, thermal conductivity (k) = $27.0 Jm^{-1}s^{-1^\circ}K^{-1}$, and density ($\rho$) = $4.51 g/cm^3$. (Hint: use the appropriate simplified solution to the generalized heat flow equation by Rosenthal.)

4. For the same sheet dimensions, joint design, and process conditions as in Problem #3, calculate and plot the peak temperatures at the same locations if the material were pure copper (ETP Cu) instead of CP Ti, assuming the following properties: melting temperature = 1083°C, thermal diffusivity (α) = 9.6×10^{-5} m^2-s^{-1}, volume specific heat capacity (ρCc) = $4.5 \times 10^6 Jm^{-3^\circ}K^{-1}$, thermal conductivity (k) = $384.0 Jm^{-1}s^{-1^\circ}K^{-1}$, and density (rho) = $8.96 g/cm^3$. (Hint: use the appropriate simplified solution to the generalized heat flow equation by Rosenthal.)
5. For a 2.5-mm-thick sheet of 0.5% plain carbon steel (which can be treated as an Fe–C binary alloy), calculate the width of the heat-affected zone (HAZ) at the point where any austenite would form for a weld made at a current of 200A, a voltage of 10v, and a mechanized welding velocity of 5 mm/second using GTAW for which the transfer efficiency is 0.65. Assume the melting temperature of 0.5% C steel is 1800°K and the eutectoid transformation temperature (at which austenite just begins to form) is 1000K. The thermal diffusivity (α) is 9.1× $10^{-6}m^2s^{-1}$, the volume specific heat capacity (ρC) is $4.5 \times 10^6 Jm^{-3^\circ}K^{-1}$, and the thermal conductivity (k) is $41.0 Jm^{-1}s^{-1^\circ}K^{-1}$. Use Rosenthal's solution for 2-D or 3-D heat flow, as appropriate, and the empirical equation for HAZ width (under "Peak Temperature"), and compare answers.
6. For the weld in Problem #5, calculate the cooling rate in this workpiece 0.25 mm from the very edge of the fusion zone (FZ) and at the edge of the HAZ where austenite just formed. If the critical cooling rate for 0.5% C steel is 90°K/second, will untempered martensite form in the HAZ of this weld? What about in the weld, if it too is 0.5% C steel? (Hint: use the empirical equation for cooling rate.)
7. What would be the width of the HAZ (as defined in Problem #3) if a weld were made by EBW using 15.0 kv beam voltage, 100 ma beam current, and 900 mm/minute welding speed? Assume the transfer efficiency for EBW is 90%. Use Rosenthal's solution for 2-D or 3-D heat flow, as appropriate, and the empirical equation for HAZ width (under "Peak Temperature"), and compare answers.
8. What would be the cooling rate 0.25 mm from the FZ boundary and at the edge of the HAZ where austenite would just have formed in Problem #7? Would untempered martensite form if the critical cooling rate were 90°K/second? (Hint: use the empirical equation for cooling rate.)
9. How would pre-heating the workpiece in Problem #7 to 260°C change the cooling rate at both locations above? Would untempered martensite form if the critical cooling rate were 90°K/second? (Hint: use the empirical equation for cooling rate.)
10. What are the possible sources of nitrogen, oxygen, and hydrogen in a molten weld pool made by the GMAW process? Are there any other possible sources if the SMAW process is used instead? If so, what are these differences?

11. What are the possible sources of hydrogen in a molten weld pool made by FCAW during maintenance welding on an offshore oil-drilling platform located in the North Sea during a driving snowstorm? Bonus: If this process was being used to repair-weld a medium carbon, low-alloy steel (with, say, 0.4C, 2.0Cr, 1.0Ni), what might the welder expect to occur differently from in an indoor, heated shop?
12. The composition of the fusion weld is affected by dilution by the base metal. For a joint like the one shown to scale below, estimate the composition of a weld made in 0.4% C plain carbon steel if an 18% Cr, 8% Ni austenitic stainless steel filler is used. Assume the plain carbon steel is a simple Fe–C binary and the stainless steel is a simple Fe–Cr–Ni ternary. (Hint: use some repeatable technique for quantitatively estimating the relative area of base metal making up the final weld.)

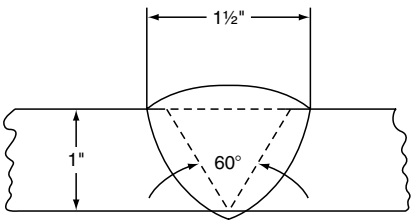


Figure P9.12

13. How does the relative size of a weld pool change for a given energy input as the weld is made in an austenitic stainless steel versus a plain carbon steel? Explain this change and give a semi-quantitative estimate of the difference(s) expected. What if the weld were made in pure copper instead of pure aluminum? Explain this change and give a semi-quantitative estimate of the difference(s) expected.
14. Explain why the weld pool of a fusion weld changes from an elongated ellipse to a distinct tear-drop shape (i.e., with a straight-sided triangular tail) at some value of welding velocity. (This is a tough one!)
15. Explain how the structure in the weld shown in the following illustration probably developed. (This is a tough one!)

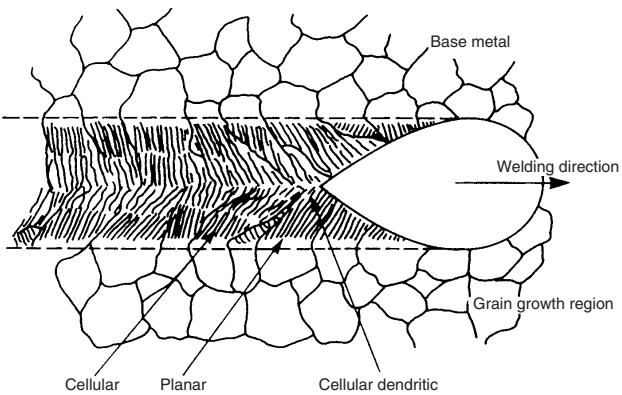


Figure P9.15

16. The new structure formed in a fusion weld upon solidification grows competitively, attempting to have preferred crystallographic growth directions align with maximum temperature gradients. Carefully sketch the pattern of growth you would expect if all the grains in the base metal had their easy-growth directions aligned parallel to the welding direction and the weld pool were essentially circular. (Hint: do not forget that the weld pool moves as growth progresses from each FZ boundary toward the weld's centerline, so the direction of the maximum temperature gradient changes.)
17. Carefully sketch the expected microstructure of a joint made in a heavily cold-worked pure metal from the FZ boundary through the HAZ to the unaffected base metal. Superimpose in this sketch a plot of the expected hardness.
18. Explain the differences in expected hardness (or strength) for a fusion weld made in a precipitation-hardening alloy if (a) the weld was made in the optimally aged (fully hardened) condition versus (b) in a solution-treated and quenched condition and then aged using the same temperature and time used in (a).
19. A low alloy steel containing 0.4% C, 0.75% Mn, 0.30% Si, 1.83% Ni, 0.8% Cr, and 0.25% Mo is to be welded. Would you be concerned about the possibility of cold cracking? If not, why not? If so, what would you do to minimize the chances of such cracking?
20. In a typical brazed joint, joint elements are overlapped and the braze filler is caused to melt in (or melt and flow into) the close-fitting gap between these elements, where it solidifies. The resulting brazed joint consists of a relatively thin layer of braze alloy sandwiched between what are often thin sheets. Thus, heat flow in such joints is almost always one-dimensional, with heat being extracted through the faces of the joint elements. Presuming this is the case, explain how this would affect the resulting solidification structure of the brazed joints.

Bonus Problems:

A. Explain how the "seeding" of clouds with silver iodide crystals is done to try to make it rain. (Hint: think about how nucleation of liquid water from water vapor in the air must occur.)
B. Describe how one would go about solving the generalized heat flow equation for a full, 3-D condition, where the various thermal–physical properties (e.g., density, thermal conductivity, specific heat) are all strong functions of the temperature and not constant. (Hint: you can, and probably should, imagine how a computer could be used to solve this problem.)

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Chapter 10

Other Joining Processes: Variants and Hybrids

10.1 INTRODUCTION TO VARIANT AND HYBRID JOINING PROCESSES

While three forces make possible the joining of materials and the structures they comprise (i.e., mechanical, chemical, and physical), these can actually be reduced to two fundamental mechanisms: pure mechanical interlocking and atomic-level bonding. The use of purely mechanical forces based on interlocking is the basis for mechanical joining processes, including the subsets of mechanical fastening and integral mechanical attachment. Interlocking can occur naturally at the microscopic level as the result of ever-present surface topological features or asperities. Interlocking can also be the result of macroscopic features that occur naturally (as in the shapes of stones making up a wall) or are designed- and processed-in (as dovetails and grooves in lumber or surface knurling of metal). The use of atomic-level bonding is the basis for two broad and similar but subtly different categories of joining: welding (with its subcategories of brazing and soldering) and adhesive bonding. Welding involves atomic-level bonding solely as the result of the natural tendency of atoms to attract one another to equilibrium spacings, at which point the force of attraction between permanent or induced dipoles is exactly balanced by the force of repulsion as outer electron shells begin to encounter one another. No chemical reaction is necessary, as neutral atoms bond by either covalent or metallic (or extended covalent) bonding in some ceramics and glasses and within the long-chain molecules of polymers or in metals, respectively. Already present, oppositely charged ions (negative anions and positive cations) bond by ionic bonding in ceramics. Already existing molecules bond by secondary bonding mechanisms having their origin in permanent and induced dipoles, as in polymers, for example. Adhesive bonding, on the other hand, involves atomic-level bonding but usually as the result of some chemical reaction. Examples are thermally activated entangling of the long-chain molecules in thermoplastic polymers, the cross-linking between long-chain molecules in thermosetting polymers, and the hydration between particles of mineral ceramics within cement.

Table 10.1 Variant and Hybrid Joining Processes

Variant Joining Processes	
Braze welding	Variant of brazing and/or fusion arc or oxy-fuel welding
Thermal spraying (THSP)	
- Flame spraying (FLSP)	Variant of oxy-fuel gas welding, brazing, or soldering
- Plasma spraying (PSP)	Variant of plasma arc welding
- Electric arc spraying (ASP)	Variant of electric arc welding
- Detonation flame spraying (DFSP)	Variant of oxy-fuel gas welding
Hybrid Joining Processes	
Rivet-bonding	Hybrid of riveting and structural adhesive bonding
Weld-bonding	Hybrid of spot welding and structural adhesive bonding
Weld-brazing	Hybrid of spot welding and brazing

The processes of mechanical joining, adhesive bonding, and welding, along with brazing and soldering, represent the overwhelming majority of all joining methods, and certainly represent all of the fundamental approaches. As has been shown, there are many different embodiments of these fundamental approaches in specific processes. There are, however, some important variations or variants and hybrids[1] of these fundamental processes. *Variants* achieve joining just like any of the fundamental processes, but they use some unusual means for doing so. Variants look like a fundamental process, for the most part, but exhibit some unusual characteristics or attributes. Just as a legless lizard may look like a snake, it is really still a lizard. *Hybrids,* on the other hand, combine fundamental processes (or specific processes within a fundamental process) to achieve some unique characteristics or capabilities, often with synergistic results.[2] Hybrids tend to be neither "fish nor fowl," something like a platypus. These variants and hybrids tend to be of more recent origin and have often been developed to overcome particular shortcomings of the basic processes for particularly challenging applications. This chapter explores these other processes.

10.2 THERMAL SPRAYING: A VARIANT JOINING PROCESS

10.2.1 General Description of Thermal Spraying

Thermal spraying (THSP) is a process in which a material is heated and propelled in particulate or "atomized" form onto a substrate. Initially, the material may be in the form of a powder, or it may be in the form of a continuous solid wire or rod. In either case, a source is needed to heat this material to either a molten or, simply, a plastic solid state. For particulate or powdered materials, heating is usually only needed to soften the

[1] A *hybrid* is something of mixed origin or composition.

[2] *Synergism* or *synergy* means the action of two or more substances, organisms, or processes to achieve an effect of which each is individually incapable, with the net effect being better than the simple sum of the effects of each individual.

particles. For continuous solid wires or rods, heating needs to be so intense that it causes melting and allows the molten material to be dispersed into small molten particles by a process known as "atomization."[3] The source of heating can be an oxy-fuel gas flame, an electric arc or plasma, or an explosive gas mixture. Heated powder particles or atomized particles from wires or rods are propelled from the heat source, called a "spray gun" or "spray torch." They are heated either during the process of their formation, if the starting form is a wire or rod, or while they are immersed in the flame, arc, plasma, or combustion jet, if the starting form is a powder. In either case, bonding to a substrate is facilitated by both the kinetic energy of the particles (which largely converts to heat upon particle impact with the substrate) and by their inherent heat. Figure 10.1 shows thermally spraying being performed in a typical industrial application.

The thermal spraying process is sometimes called "metallizing" or "metal spraying," but it is really broader than these terms denote. Most metals, their oxides and carbides, ceramic–metal mixtures (called "cermets"), or hard metallic or intermetallic compounds can be deposited by one or more of the various process embodiments of thermal spraying to be described in Subsection 10.2.5. It is also possible to thermally spray and deposit thermoplastic polymers.

The thermal spraying process is a joining process in the sense that it joins one material to another on a macroscopic or bulk scale using microscopic or atomic-level

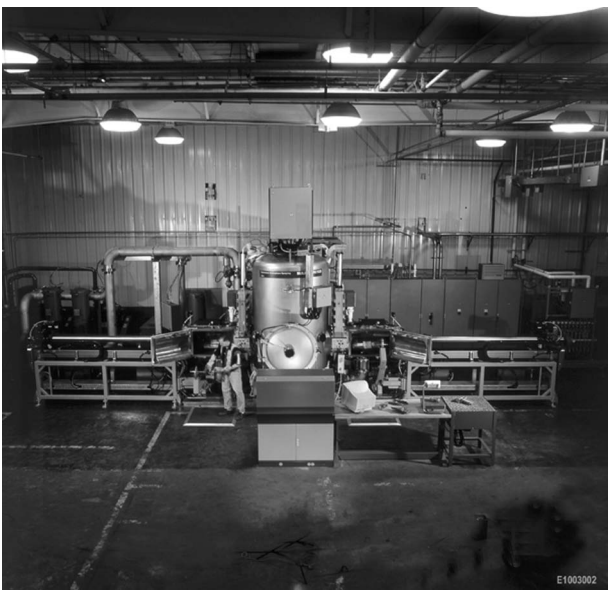

Figure 10.1 A complex and sophisticated low-pressure plasma arc (LPPA) spraying system used for applying oxidation and erosion protection coatings to gas turbine components. (Courtesy of Howmet Castings, Darien, CT, with permission.)

[3] *Atomization* of materials into particulate forms or powders is usually accomplished by causing a fine stream of molten material to break up into small, individual droplets because of the impingement of a jet of air or inert gas or a stream of water.

mechanisms. Although usually used for applying protective surface coatings (not unlike welding or brazing for the purpose of hard-facing or surfacing[4]), thermal spraying can be used for more traditional joining of actual parts in combination with brazing or adhesive bonding. In these cases, it is used to simply apply a braze alloy or a thermoplastic adhesive by spraying, and then the process of brazing or bonding is completed by heating that deposit under some pressure in a process generically referred to as "fusing." The thermal spraying process can also be used to produce solid objects using a disposable substrate, form or mandrel, or mold onto or into which material is spray-deposited. The finished object is often near-net shape. Here, thermal spraying is a shape-welding process.

So, thermal spraying is definitely a variant process—possibly a variant of welding, possibly a variant of brazing, and, in some applications, possibly a variant of adhesive bonding.

10.2.2 Mechanism of Thermally Sprayed Coating Adhesion

When molten or softened particles strike a substrate at high velocity, they flatten in the direction of motion and form thin platelets that conform to the substrate surface contour. These platelets cool very rapidly and solidify (for molten metals or ceramics), or simply harden (for softened metal or thermoplastics). Successive layers are built up until the

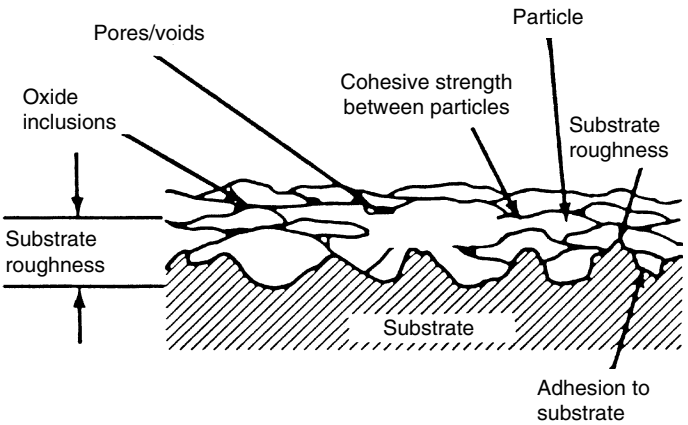

Figure 10.2 Schematic illustration showing the mechanism of thermally sprayed coating adhesion. (Reprinted from the *Welding Handbook*, 8th ed., Vol. 2, *Welding Processes*, Fig. 28.2, page 865, American Welding Society, Miami, FL, 1991, with permission of the American Welding Society.)

[4] *Hard-facing* involves the application of a material, usually a hard metal alloy or ceramic, to the surface of a part for the express purpose of improving the wear-resistant properties of that part. "Surfacing" is a more general process involving the application of a material to the surface of a part for improving either wear or corrosion or some other surface property (e.g., providing a gripping surface, adding decoration or a decorative finish, etc.). In welding and brazing, this coating is applied in the molten state. In thermal spraying, the material being applied may be molten or may be only soft and plastic.

desired thickness is obtained by having sprayed particles bond to one another, as opposed to the substrate. Figure 10.2 schematically illustrates how particles are propelled toward a substrate, deform upon impact (giving up their kinetic energy in the form of heat), conform to the contour of the substrate, and adhere. The almost inevitable entrapment of voids, oxides, and other inclusions is also apparent in Figure 10.2.

The bond between the sprayed deposit and the substrate may be mechanical (i.e., involving only interlocking), metallurgical (i.e., involving welding), chemical (i.e., involving a reaction), or a combination of these, depending on the nature of the material being sprayed, the substrate, and the process spraying conditions. Ideally, the kinetic energy of the propelled particles brings the materials into intimate contact and ruptures any oxide layers on the particle or droplet or the substrate, thereby causing atomic-level bond formation. It uses the heat from initial heating as well as from conversion of kinetic energy to accelerate the kinetics of diffusion and/or reaction with the substrate surface. In some cases a thermal treatment of the resulting layered structure is used to increase the bond number, extent, and strength by diffusion and/or cause chemical reaction between the deposit and the substrate. As stated previously, this is called "fusing." Obviously, there is always the possibility of (and sometimes there is only) mechanical interlocking of particles to the substrate or to one another. This can happen because there is a fundamental incompatibility between the coating material and the substrate, or, more often, it can be the result of improper preparation of the substrate and/or improper operating conditions for the spraying process. If the substrate is not properly precleaned prior to spraying or cleaned by the impinging particles, or if the particles are not moving fast enough or are not hot and soft enough or are oxidized, proper atomic bonding cannot take place. What will happen is that impinging particles will deform to match and mate with the contour of the material that they impact, and, in doing so, will mechanically lock together. Mechanical adhesion is usually not enough, however.

The strength of the bond between the sprayed coating and the substrate depends on the following factors: (1) the substrate material's inherent tendency to bond with the coating material (i.e., their chemical compatibility) and its tendency to oxidize; (2) the substrate's geometry (severity of contour); (3) the substrate's surface preparation (which means cleanliness and roughness to facilitate chemical and mechanical bonding, respectively); (4) the angle of spray particle impingement (which influences sticking versus bouncing away); (5) the presence of substrate preheat (which enhances interdiffusion and/or chemical reactions between the impinging particles and the substrate); (6) the deposit thickness (which determines the state of any residual stress); and (7) post-spraying thermal treatment (which encourages and enables interdiffusion and/or reaction). Bonding between sprayed particles tends to be easier to achieve in most cases than bonding between sprayed particles and the substrate, due to the obvious compatibility between sprayed particles.[5] Sometimes initial bonding of the sprayed particles to the substrate is aided with the prior application (also by spraying) of an intermediate material before the final deposit, called a "bonding layer." Other times, the bonding

[5] Of course, bonding between even identical particles can only occur if the spraying conditions preclude unwanted oxidation of the particles' surfaces.

of sprayed powders can be enhanced through special design of the powders to cause surface layers on each particle to react with the substrate, which causes cleaning and activation (e.g., the reaction between thin, separate layers of Al and Ni to cause the formation of a Ni–aluminide bonding layer by an exothermic reaction).

10.2.3 Properties of Thermally Sprayed Coatings

The properties of the deposited and bonded coating depend on the density of the deposit, the cohesion between the deposited particles within the deposit, and the adhesion between the first particles deposited and the substrate. The density of the deposit produced by thermal spraying depends on the type of material being sprayed, the method of spray deposition, the specific spraying procedure, and subsequent processing (e.g., thermal stress relief, fusing, etc.).

Because the process is often performed with the substrate at or only slightly above room temperature, and since the direct heat and additional heat from conversion of kinetic energy transferred by the particles as they strike the substrate are relatively small (on a bulk scale), there is usually little thermal alteration of the substrate. For this reason, thermal spraying is excellent for restoring dimensions by replacing material lost by wear or corrosion, or for applying a protective coating against wear or corrosion. The process is especially good for creating unique surface microstructures such as composites (e.g., intimate mixtures of metals and ceramics) and amorphous, rapidly solidified alloys.[6]

10.2.4 Applications of Thermal Spraying

Thermal spraying is most widely used for surface alteration. Surface deposits can be applied to restore dimensions where material has been lost by wear or corrosion, or to apply material to dies or molds or castings to achieve precise dimensions not achieved in initial fabrication. They can also improve surface resistance to wear, corrosion, oxidation, or combinations of these by adding a surface layer that is different in composition and structure than the underlying material. Zinc, aluminum, stainless steel, bronze, hard alloys (i.e., carbides, borides, aluminides, etc.), and ceramics are used. Because of its ability to restore dimensions and protect surfaces, thermal spraying is a valuable and widely used process in maintenance and repair, as well as in original equipment manufacturing (OEM).

Thermal spraying can also be used to provide certain other desired properties, such as thermal or electrical conductivity or insulation, high friction for traction (such as on stair and walking surfaces on the decks of ships, where water can make those surfaces slippery), or lubricity through the application of a polymer to a metal. An increasingly important application of the process is the spray consolidation of

[6] By very rapidly cooling some complex, multi-component alloys, atoms in the liquid state do not have sufficient time to rearrange themselves into the preferred crystalline solid. They get stuck in their liquid-like (amorphous) arrangement and have unusual solid properties as a result.

reinforcing materials (e.g., filament-wound or preplaced fibers) to produce a metal- or ceramic-matrix composite part. Finally, thermal spraying can be used for joining by applying braze filler or solder or thermoplastic adhesive to a surface and then fusing that deposit under pressure to effect bonding and joining of another part.

10.2.5 Different Methods of Thermal Spraying

There are four different methods or embodiments of thermal spraying: (1) flame (or combustion) spraying (FLSP); (2) plasma spraying (PSP); (3) electric arc spraying (ASP); and (4) detonation flame spraying (DFSP). These variations are based on the method by which material being sprayed is heated to the molten or softened plastic state and the technique for propelling the resulting hot particles to impact the substrate.

In *flame spraying,* the material to be sprayed is continuously fed into and melted or softened by an oxy-fuel gas flame or combustion flame. This variation is also known as *combustion (flame) spraying*. A typical flame spray gun or combustion torch is shown schematically in Figure 10.3. The material feedstock may initially be in wire, rod, or powdered form. Obviously, for wire or rod forms, sufficient heating by the flame must occur to cause melting and allow atomization of the molten material into particles, usually using the jet action of the rapidly expanding combusted gases as they exit the torch nozzle. For powders, on the other hand, heating in the flame may (but need not) cause melting. Regardless of the starting form of the feed material, molten or softened particles are propelled onto a substrate by either an auxiliary air jet or the combusted and rapidly expanded gases themselves.

The heat value of an oxy-fuel combustion flame is limited compared to other sources, although modern torch designs have enabled heat values of greater than 100,000 BTUs[7] to be achieved. Because of limited heat values, there are some practical

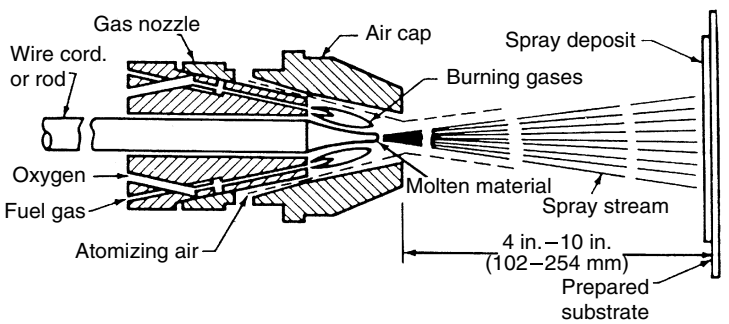

Figure 10.3 Schematic illustration of a typical flame or combustion flame spraying torch or gun. (Reprinted from the *Welding Handbook,* 8th ed., Vol. 2, *Welding Processes,* Fig. 28.4, page 869, American Welding Society, Miami, FL, 1991, with permission of the American Welding Society.)

[7] A *BTU* is a British Thermal Unit, representing the amount of heat needed to raise one pound of water one degree Fahrenheit.

Table 10.2 Materials That Can Be Thermally Sprayed by Various Methods

Flame-Sprayed		
Metal wires	*Ceramic rods*	*Powders*
Aluminum	Alumina–titanium	Hard metals
Copper	Alumina	Carbides
Molybdenum	Zironia	Borides
AISI 1025 steel	Rare earth oxides	Oxides
304 stainless steel	Zironium silicate	Nitrides
Zinc	Magnesium zironate	Thermoplastics
	Barium titanate	
	Calcium titanate	
	Chromium oxide	
	Magnesia–alumina	
	Mullite	

Electric Arc-Sprayed	
Aluminum	Stainless steel
Copper	Mild steel
Brass or bronze	Babbit metal
Zinc	

Plasma-Sprayed		
Metals	*Ceramics*	*Cermets*
Aluminum	Cr–carbides	Alumina–nickel
Chromium	Ti–carbides	Alumina–nickel aluminide
Copper	W–carbides	Magnesia–nickel
Columbium (Niobium)	Alumina	Zirconia–nickel
Molybdenum	Cr–oxides	Zirconia–nickel aluminide
Nickel	Magnesia	
Nickel–chromium	Titania	
Tungsten		
Tantalum		

Detonation Flame Sprayed	
Alumina	Tungsten carbide/Co binder
Alumina–titania	Tungsten carbide/Ni–Cr binder
Chromium carbide/Ni–Cr binder	Tungsten chromium carbide/Ni–Cr binder

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limitations on the types of materials that can be sprayed by this method. Refractory metals or ceramics can be difficult or impossible to spray. In addition, the velocity that can be obtained is also limited (although it is always very high and is sometimes supersonic). Thus, the as-deposited density and adhesion can be limited. Table 10.2, while not exhaustive, lists materials that can be flame-sprayed.

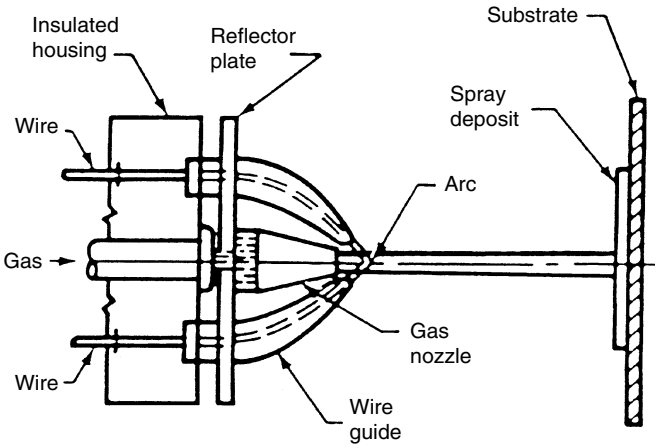

Figure 10.4 Schematic illustration of an electric arc spray torch or gun. (Reprinted from the *Welding Handbook,* 8th ed., Vol. 2, *Welding Processes,* Fig. 28.9, page 873, American Welding Society, Miami, FL, 1991, with permission of the American Welding Society.)

In *electric arc spraying,* two continuously fed wires are melted by an electric arc sustained between them. This arc heats the wires to melting and atomizes the material into particles through the pinching effect of the Lorentz electromagnetic force. The arc force or arc jet propels the atomized particles onto a substrate, usually with the assistance of an auxiliary jet of compressed air. A typical arc spray gun is schematically illustrated in Figure 10.4. This method is restricted in use to metals or alloys that can be produced as continuous wires. Deposited densities are not particularly impressive, and there can be contamination from oxidation of the spray particles. Table 10.2 lists some of the important materials that can be electric arc–sprayed.

In *plasma spraying,* the heat for melting or softening the material being sprayed is provided by a non-transferred plasma arc. Such an arc (described in Subsection 6.4.3 of Chapter 6) is maintained between the non-consumable tungsten electrode and the constricting inner nozzle of a torch. A typical plasma spray gun is shown schematically in Figure 10.5. An inert or reducing gas, under pressure, enters the annular space around the electrode, where it is heated to a very high temperature (typically above 10,000°K) by the arc. The extremely hot gas is ionized and expanded tremendously, so that it passes through and exits from the nozzle as a very high- (often supersonic-) velocity jet. The material being sprayed is usually injected in powdered form into the hot gas jet, where it picks up heat and melts or softens while being propelled onto the substrate surface. The inherently higher heat value of plasma spray systems allows essentially any material to be sprayed, no matter how refractory. Further, the very high kinetic energy imparted to the spray particles results in more adherent and denser deposits. Table 10.2 lists some important types of materials that can be plasma-sprayed.

The *detonation flame spraying* method operates on a very different principle from the other thermal spray methods. Charges of powdered material are repeated-heated and projected as molten or plastically softened particles onto a substrate by rapid, successive detonations of an explosive mixture of acetylene and oxygen in a gun

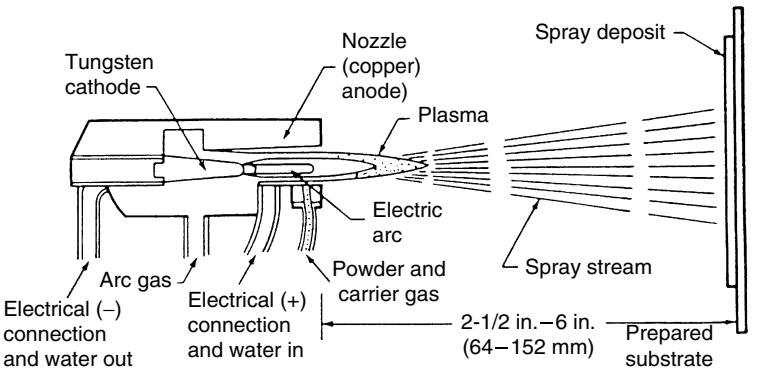

Figure 10.5 Schematic illustration of a plasma spray torch or gun. (Reprinted from the *Welding Handbook*, 8th ed., Vol. 2, *Welding Processes*, Figure 28.10, page 874, American Welding Society, Miami, FL, 1991, with permission of the American Welding Society.)

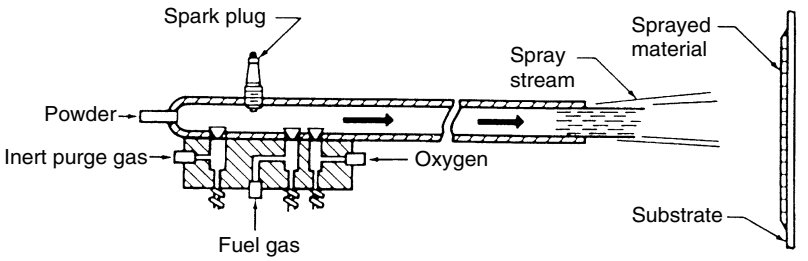

Figure 10.6 Schematic illustration of a detonation flame spray gun. (Reprinted from the *Welding Handbook*, 8th ed., Vol. 2, *Welding Processes*, Fig. 28.8, page 873, American Welding Society, Miami, FL, 1991, with permission of the American Welding Society.)

chamber (see Figure 10.6). The particles leave the gun at much higher velocities than in other processes, thereby producing much denser deposits. The process may not (and usually does not) produce the amount of heating that other processes do, however, as the dwell time of particles in the hot gas jet is very short. Table 10.2 lists some materials sprayed by the detonation flame–spraying method.

Table 10.3 compares the various thermal spraying processes in terms of heat source temperature, particle velocity, and types of materials that can be sprayed.

10.3 BRAZE WELDING: BRAZING OR WELDING?

Braze welding is another odd process—neither brazing nor welding, but a variant of one or the other. It is accomplished by the use of a filler metal having a liquidus above 450°C (840°F) and below the solidus of the base metal(s) to be joined, fulfilling one of the key requirements of brazing as opposed to welding, whether by fusion or nonfusion. However, unlike brazing, in braze welding the filler is *not* distributed in the joint

Table 10.3 Comparison of Various Thermal Spray Process Characteristics

	Flame Oxyfuel gas combustion	*Detonation Oxyfuel gas pulsed explosion*	*Arc Electric arc, Two wires*	*Plasma Nontransferred arc*	*PTA Plasma transferred arc*
Heat source temperature	4,700–5,600°F	6,000°F +	8,000°F	15,000°F	15,000°F
Particle velocity	800 ft/sec	2500 ft/sec	800 ft/sec	1800 ft/sec	—
Coating Materials					
Wire-metal	Yes	No	Yes	Yes	Yes
Powder-metal	Yes	Yes	No	Yes	Yes
Powder-ceramic	Yes	Yes	No	No	No
Rod or cord ceramic and plastic	Yes	No	No	No	No

From: *Modern Welding Technology*, 2e, Howard B. Cary, 1989, pages 220, 221, 222, with permission of Prentice-Hall, Englewood Cliffs, New Jersey.
Compiled from data found in *Modern Welding Technology*, 2nd ed., by Howard B. Cary. Englewood Cliffs, NJ, Prentice Hall Publishing, pages 220, 221, and 222, 1989.

by capillary action but, rather, is added to a prepared joint as a consumable rod (analogous to rods used with oxy-fuel gas welding) or as a consumable electrode (analogous to shielded metal-arc welding). Typical of brazing, however, the base metals are not melted; only the filler is. Bonding in braze welding takes place between the deposited filler and the hot (but not melted) base metals in the same manner as in conventional welding or brazing (i.e., through the formation of metallic bonds during interdiffusion or reaction at the faying surfaces of the substrates and the filler). Figure 10.7 schematically compares braze welding, fusion welding, and brazing.

Joint designs for braze welding are similar to those used in oxy-acetylene welding and are typically grooved butt configurations or fillets made with or without bevels. To obtain a strong bond between the filler and the unmelted base metal(s), the molten filler must wet the hot base metal(s), with some attendant interdiffusion or dissolution. The process involves heating the base metal joint elements to the temperature at which the braze filler melts and flows, adding flux (for the oxy-fuel process embodiments), precoating the joint faces with the filler alloy (in a process known as "buttering"), and then continuing to add filler until the joint is completely filled. For fillet braze welding, buttering is not necessary, although it can help.

Most braze welding is done using an oxy-fuel gas welding torch, but the process can be done using a non-consumable carbon arc, gas–tungsten arc, or plasma arc torch. Carbon arcs were once widely used with zinc-galvanized steel. Gas–tungsten and plasma arcs tend to be used with inert gas shielding and with filler metals that have relatively high melting temperatures that need the heat intensity of these arc/plasma sources. Specially formulated shielded consumable electrodes can also be used with shielded metal-arc welding.

The braze welding process has some distinct advantages over conventional fusion welding processes. First, less heat is required to accomplish bonding than with conventional welding, thereby permitting higher joining speeds, less energy consumption, and

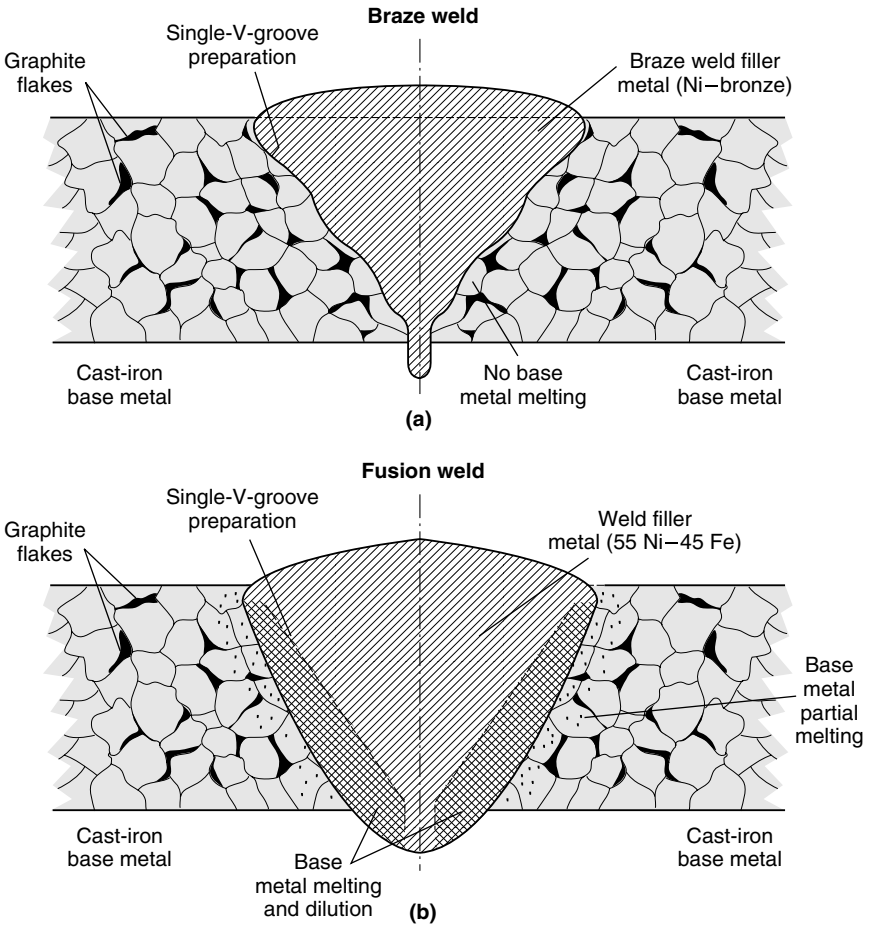

Figure 10.7 Schematic comparison of braze welding (a) and fusion welding (b).

less distortion. Second, the deposited filler metal is relatively soft and ductile, thereby providing good machineability (for removal of a convex weld crown and/or root, known as ''reinforcement'') and low residual stresses. Third, joints can be produced with adequate strength for many applications. Fourth, brittle metals (sensitive to thermal shock cracking), such as gray cast iron, can be braze welded without extensive preheating and minimal tendency toward cracking. Fifth, the process provides a convenient way to join dissimilar metals (e.g., copper to steel or cast iron, and nickel–copper alloy to cast iron or steel). Sixth, the equipment required for braze welding is relatively inexpensive and easy to use.

Despite these numerous advantages, there are disadvantages. First, the strength of braze welds is limited to that of the filler metal, which, since melting temperatures are lower than the base metal(s), tends to be weaker. Second, permissible service temperatures for braze-welded assemblies are lower than those for fusion-welded

Table 10.4 Some Typical Braze Welding Fillers

AWS Classification	*Chemical composition (wt. of %)*					*Minimum tensile strength*		*Liquid temperature*	
A 5.7 and A 5.8	*Cu*	*Zn*	*Sn*	*Fe*	*Ni*	*MPa*	*ksi*	*°C*	*°F*
RBCuZn-A	60	39	1	—	—	275	40	900	1650
RBCuZn-B	60	37.5	1	1	0.5	344	50	890	1630
RBCuZn-C	60	38	1	1	—	344	50	935	1630
RBCuZn-D	50	40	—	—	10	413	60	935	1715

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr. Stoneham, MA, Butterworth-Heinemann, page 379, Table 10.3, 1993, with permission of Elsevier Science.

assemblies, again because of the lower-melting fillers employed. Third, the joint may be subject to galvanic corrosion or differential chemical attack due to the filler–base metal mismatch. Fourth, the color of the braze weld may not match the base metal, which, for some applications, might be a concern.

Filler metals used for braze welding tend to be commercial torch brazing brass filler alloys containing approximately 60 wt.% Cu and 40 wt.% Zn, with small additions of Sn, Fe, Mn, and Si to improve flow characteristics, decrease volatilization of Zn, scavenge O, and increase strength and hardness. Nickel additions of up to 10 wt.% whiten the color of brasses (i.e., Cu–Zn alloys) and bronzes (i.e., Cu–Sn alloys) and increase strength and corrosion resistance. Some typical braze-welding fillers are listed in Table 10.4.

Fluxes for braze welding are formulated for the base metal(s) and the filler metal, often a brass or bronze. They tend to remain active for longer periods of time at higher temperatures than fluxes designed for capillary brazing, since that is demanded by the nature of the process.

Joints for braze welding are usually of groove, fillet, or edge type, similar to those used for conventional fusion welding. Assemblies can be simple or complex and can be made up of sheet, plate, pipes, tubes, rods, bars, forgings, castings, or powder compacted parts. For best strength, the bond area between the brazing alloy and the base metal should be as large as possible.

10.4 HYBRID JOINING PROCESSES

10.4.1 General Description of Hybrid Joining Processes

There are some *hybrid joining processes* in which two different fundamental processes are combined to create a new process with extended capability. Sometimes the resulting hybrid simply combines the characteristics or attributes of both of the parent processes, hoping to obtain the best of both. Some would say braze welding is an example, although it is contended here that braze welding is a variant of welding or of brazing, not a hybrid. At other times the hybrid exhibits unique benefits as the result of

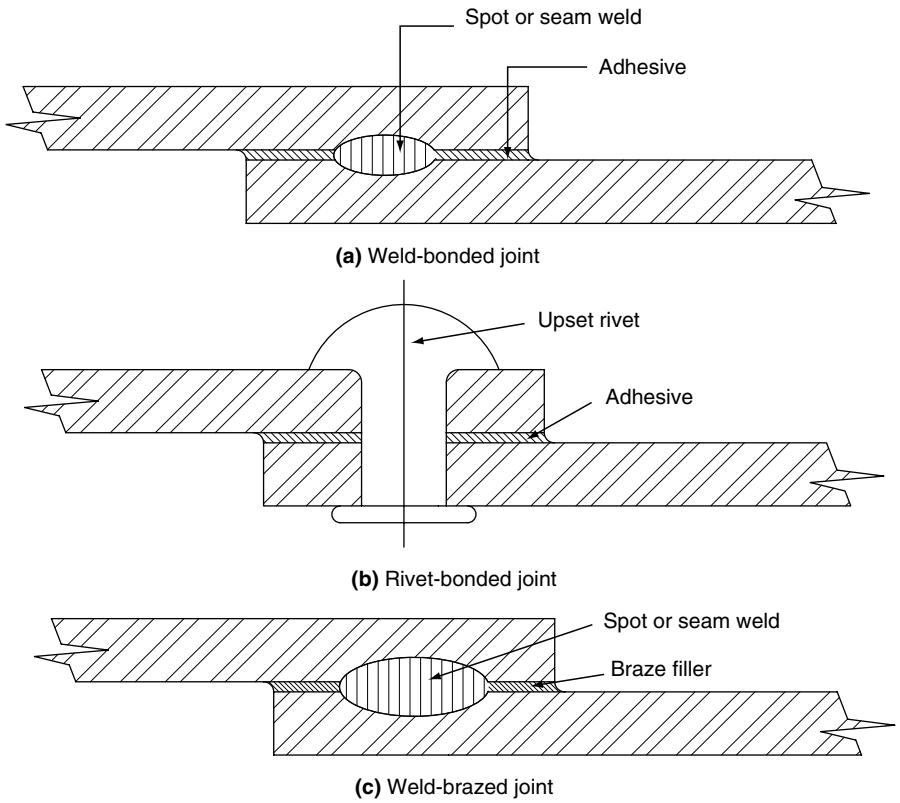

Figure 10.8 Schematic illustrations of joints produced by various hybrid joining processes: (a) weld-bonding, (b) rivet-bonding, and (c) weld-brazing.

synergy between the two parent processes. This should be the goal, in fact. Three examples of hybrid processes are (1) rivet-bonding, (2) weld-bonding, and (3) weld-brazing. Not every combination of basic joining processes necessarily results in a useful hybrid, no more than every attempt at interbreeding different animal or plant species results in a better hybrid animal or plant. In fact, there are some process combinations that can cause problems.

Figure 10.8 schematically illustrates the most common hybrid joining processes.

10.4.2 Rivet-Bonding

Rivet-bonding is a hybrid of adhesive bonding and mechanical joining employing rivets as fasteners. Shown schematically in Figure 10.9, the combination of rivets driven and set though structural adhesive has been used to considerable advantage in helicopter manufacturing, as an example. The rivets tend to carry any transient out-of-plane loads (whether anticipated or unexpected) to protect the adhesive from failing in peel. On the other hand, the adhesive acts to spread loading and soften stress concentrations

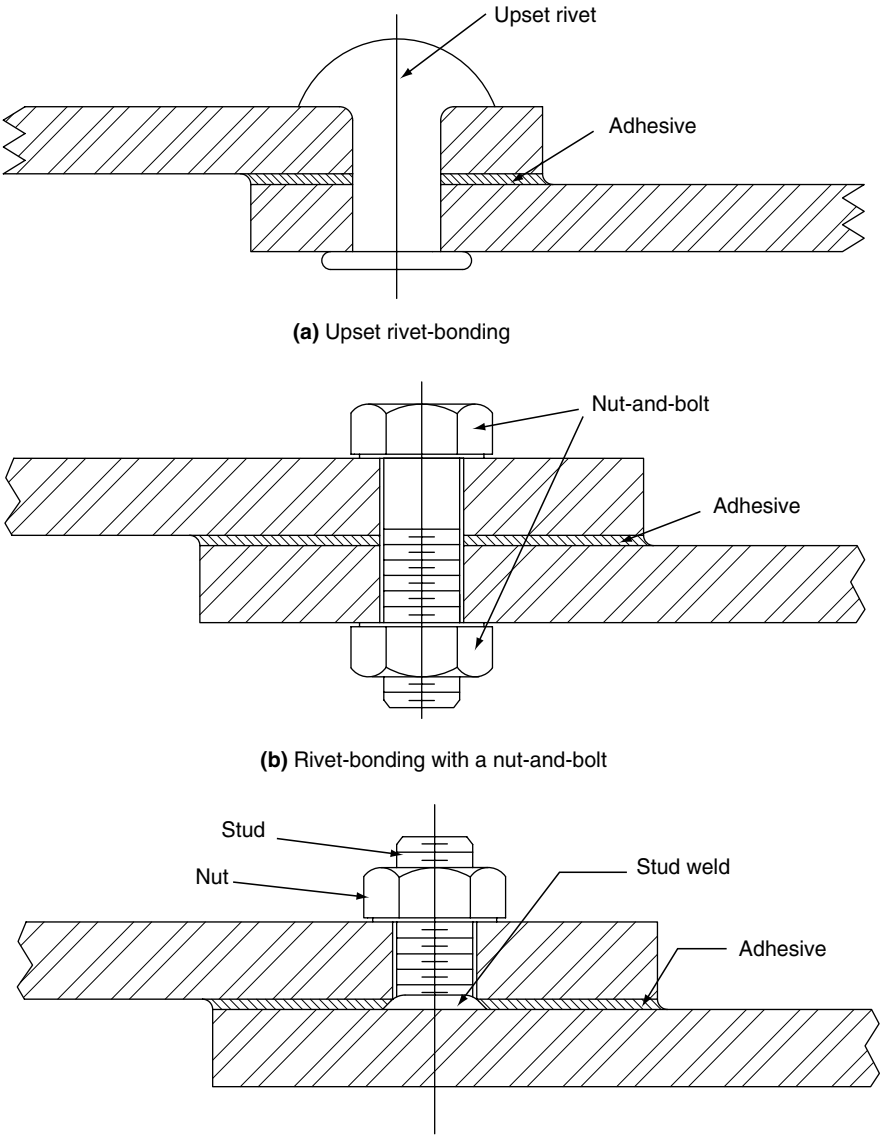

Figure 10.9 Schematic illustration of rivet-bonding in a lap joint using an actual upset rivet (a), a nut and bolt (b), or a stud-arc or percussion-welded threaded stud and nut (c). Note that rivets and bolts are virtually always inserted after adhesive bonding.

around the rivets, thereby improving fatigue resistance. Another particular advantage in helicopters is vibration damping. (Without adhesive, these would be riveted-only joints, with only the friction at joint faying surfaces acting to damp vibrations.) Last but

not least, a major consideration in the use of rivets with structural adhesives has been the mutual self-fixturing that results. Rivets hold adhesive-bonded structures together under pressure until the adhesive fully cures. On the other hand, quick-setting (especially pressure-sensitive "contact") adhesives can be used to tack structures together while riveting is being performed.

10.4.3 Weld-Bonding

Weld-bonding, also called "spot-weld adhesive bonding" for reasons that will soon become clear, is a hybrid method of fabricating that uses both welding and adhesive-bonding techniques. In its most common form, a layer of adhesive, in either paste or film form, is applied to one of the metal members to be joined. The other metal member is placed on top, forming a lap-type joint, and the assembly is then clamped to maintain part alignment. The two metal members are then joined by resistance welding through the adhesive using a spot welder mounted on a common C-frame (as widely used in the aerospace industry), or as a portable unit attached to the working end of a robot arm (as widely used in the automobile industry). Spot welds are typically spaced 2.5–5.0 cm (1–2 in.) apart, center to center. It is also possible, in another variation of the process, to spot weld first and then back-infiltrate the gap between the joint element faying surfaces with a thinned adhesive, relying on capillary action to cause flow and fill.

Figure 10.10 schematically illustrates a resistance spot weld in a single-lap weld-bonded joint. Spot-welding pressure and heat displace the adhesive from the immediate area where the weld is to be made and allow metal fusion to occur, forming a nugget. A visible mark on the face surface of the metal sandwich (or lap joint) sheet denotes the weld location. The inner circle outlines the weld nugget. The area between the two dashed circles in the figure, known as the "halo," is effectively unbonded because of the near total displacement of the adhesive and heating effects (e.g., adhesive softening and squeezing away, or adhesive thermal decomposition). Beyond the halo is a region of transition to full adhesive bond line thickness and adhesive bond strength.

The weld-bonding process offers some important advantages over simple mechanical fastening as well as over simple adhesive bonding. Compared to a mechanically fastened structure, a similar weld-bonded structure offers (1) increased static pure tensile and/or tensile shear strength (by increasing the total area of joining from just the area of the fasteners to the area of the welds and the surrounding adhesive); (2) increased fatigue life (by spreading the loading through the adhesive and minimizing stress concentrations around points of discrete spot welding or fastening); (3) gas-tight and/or fluid-tight joints (through the sealing action of the adhesive, whether a structural type or simply a sealant); (4) increased structural rigidity or stiffness, especially against torsion in automobile frames, for example (by preventing slip at fasteners or buckling between points of fastening or welding); (5) improved resistance to corrosion (through sealing); (6) inexpensive tooling (as tack welds or "holding" adhesives can be used); (7) weight savings (compared to fasteners); (8) smooth, hermetically sealed inner and outer surfaces (for aerodynamics); (9) enhanced energy absorption (due to the

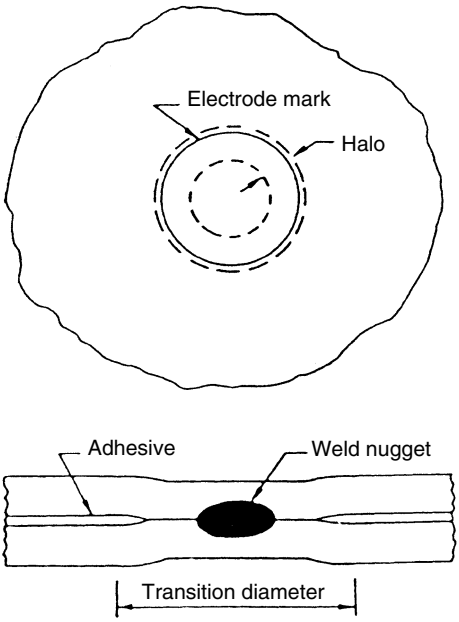

Figure 10.10 Schematic illustration of weld-bonding in single-overlap joints showing the so-called "halo" around the weld nugget, where there has been upsetting but no fusion by the resistance spot welding electrodes. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 10.6, page 374, Butterworth-Heinemann, Stoneham, MA, with permission of Elsevier Science, Burlington, MA.)

added energy needed to open the bonded plus welded or fastened joint area), which improves both the crashworthiness of automobiles and their ride quality (through vibration damping and noise abatement) and (10) complete interface bonding to improve load transfer.

While not always used with structural (as opposed to non-structural) adhesives applied for other purposes, some of the most interesting property improvements are realized with structural adhesives. Compared to pure adhesive bonding, weld-bonding dramatically increases resistance to peel and/or cleavage failure by having welds carry out-of-plane loads. It absolutely increases resistance to buckling in compression, and seemingly even increases static pure tensile and tensile shear strength. The ability of joints, and thus joined structures, to absorb impact energy is absolutely increased, often quite dramatically, by the added energy that must go into tearing open the adhesive. This improvement can be shown with the increased area under the tensile stress-strain curve for T-peel tests, as shown in Figure 10.11. There is considerable evidence that fatigue strength is higher for any needed life, or that fatigue life is increased for any design stress, seemingly from the softening of stress concentrations around discrete spot welds (or fasteners in rivet-bonded joints). What is more, the improvement in fatigue life is more than would be expected from simply adding the expected life or strength from adhesive alone or welds alone. This effect is shown in Figure 10.12.

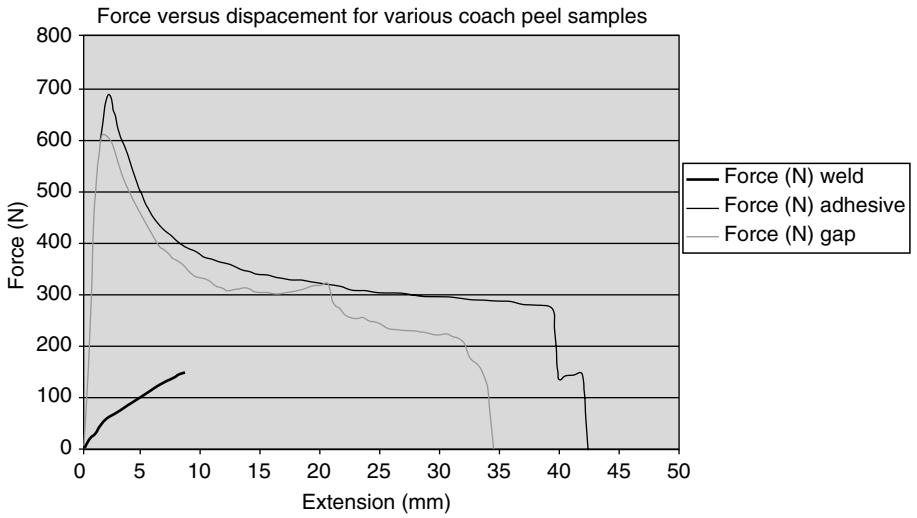

Figure 10.11 Plot of weld-bonded versus welded-only and bonded-only energy absorption in T-tension or ''coach-peel'' tests, with area under the curve corresponding to the amount of energy absorbed to failure. (From an unpublished report on weld-bonding of AA5754 using laser spot-welding, Robert W. Messler, Jr., Rensselaer Polytechnic Institute, Troy, NY, July 2002.)

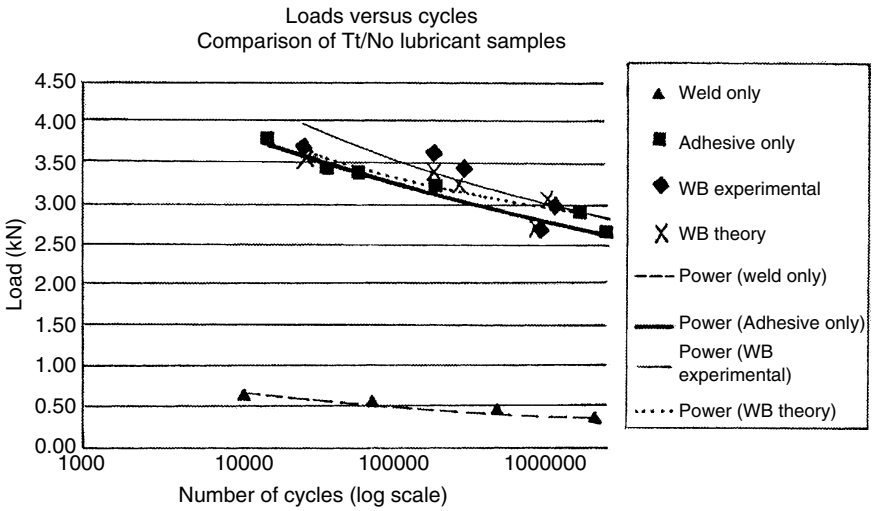

Figure 10.12 Plot of weld-bonded versus welded-only and bonded-only fatigue strength in laser-beam weld-bonded AA5754. Note that actual, experimental data points would fall above the points predicted by theory, if combining the two processes produced simply additive versus synergistic effects. (Reprinted from ''Laser beam weld-bonding of AA5754 for automobile structure'', R.W. Messler, Jr., J. Bell, and O. Craigue, *Welding Journal*, 81(6), 2003, pages 151s-159s, with permission of the American Welding Society, Miami, FL.)

Weld-bonding is competitive in static strength with titanium fasteners in sheet titanium up to 4 mm (0.156 in.) thick. Beyond this point, spot-welding limitations and static strength capacity make weld-bonds less desirable. Epoxy and polyimide adhesives are typically used for titanium, often using fillers of silica (7 wt.%), strontium chloride (3 wt.%) for corrosion resistance, and metal powder. Aluminum alloys are also weld-bonded using epoxy, modified epoxy, or elastomeric urethane adhesives, sometimes with fillers. When conductive metal-filled adhesives are used, welding parameters are nearly the same as those used for welding without an adhesive.

Resistance spot welding through an adhesive causes a high percentage of irregularly shaped nuggets, but the strength of the joints is not adversely affected. There is, however, also a tendency for a higher percentage of spot welds to exhibit "expulsion" or "spitting," in which molten metal from within the nugget is blown out from between the squeezed, overlapped joint elements due to thermally induced pressure. Such expulsion absolutely results in lower quality and lower strength welds. This has proven to be a particular challenge as automobile manufacturers have considered using laser welding instead of resistance welding to spot weld-bond aluminum alloy-intensive vehicles. The approach of welding first and then back-infiltrating with a low-viscosity (or thinned) adhesive, or of welding through prepunched openings in preplaced film adhesive, as well as some other techniques of applying localized pressure during welding, opens up new possibilities of laser-beam weld-bonding.

Use of weld-bonding has probably grown most rapidly in the automobile industry, with continuing needs and efforts to reduce vehicle weight to improve fuel economy without compromising safety or comfort (ride harshness). The increased use of aluminum alloys in vehicle bodies has provided an additional driving force for further development, with impressive demonstrations in special test and prototype vehicles.

10.4.4 Weld-Brazing

The National Aeronautics and Space Administration (NASA) and the U.S. Air Force developed the hybrid joining process of weld-brazing, in which molten braze filler was back-infiltrated between overlapped joint elements that had been spot-welded (see Figure 10.13a). Braze alloy preforms have also been used in which there are prepunched holes through which spot welds are first made, and then the braze filler is melted to flow throughout the joint, as shown in Figure 10.13b. In either variation, the process is called *weld-brazing*.

Two materials that have been weld-brazed to advantage are titanium and aluminum alloys, both using aluminum alloy braze filler (i.e., a BAlSi type). The process of weld-brazing results in demonstrable improvements in static shear and, especially, peel and fatigue strength. There is not much evidence of a synergistic effect in weld-brazing, however. Static shear strength seems to improve in a simple additive fashion, and there appears to be no gain in weld-brazed over brazed-only joints (Figure 10.14). Strength-at-temperature, on the other hand, is improved somewhat, mostly by extending service temperatures slightly beyond those for brazing alloys alone. This is

clearly due to the welds carrying most of the load to lower the stress in the braze filler. Figure 10.15a shows the tensile shear strength as a function of test temperature, while Figure 10.15b shows stress-rupture behavior, both for single-overlap specimens.

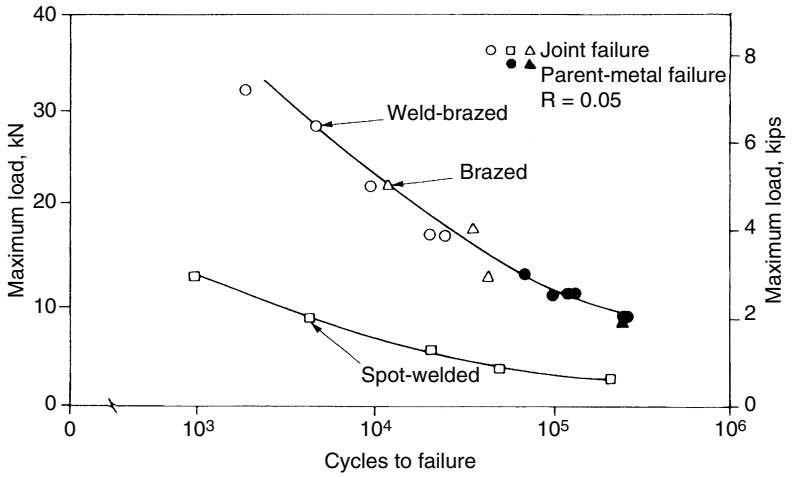

Figure 10.13 Schematic illustration of alternative approaches to weld-brazing. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 10.7, page 375, Butterworth-Heinemann, Stoneham, MA, with permission of Elsevier Science, Burlington, MA.)

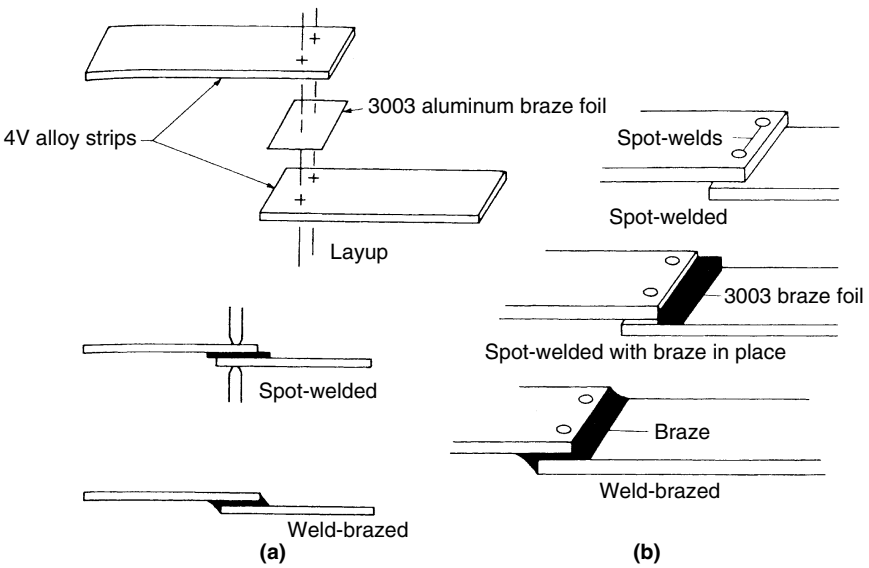

Figure 10.14 Plot of fatigue strength for weld-brazed versus brazed-only and welded-only joints. (Reprinted from *Development of the Weld-Braze Joining Process*, T.T. Bales, D.M. Royste, and W.E. Arnold, Jr., NASA Technical Note D-7281, Washington, DC, National Aeronautics and Space Administration, 1973, with permission.)

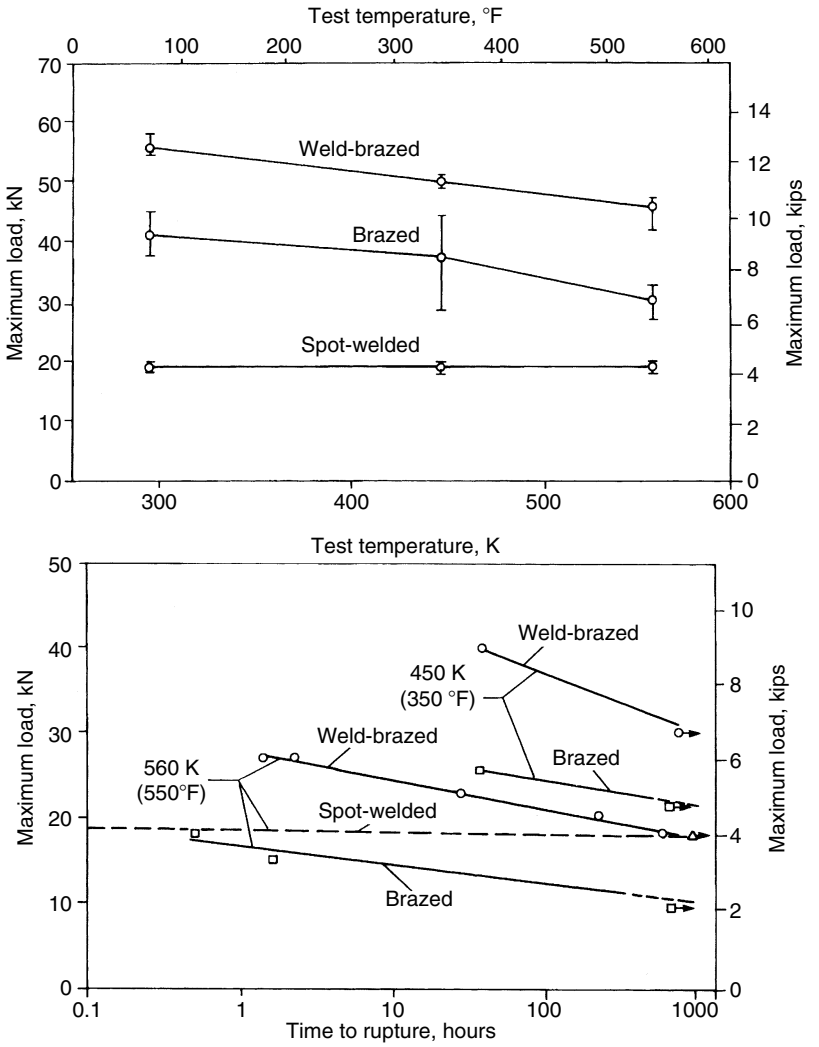

Figure 10.15 Plots of tensile-shear and stress-rupture strength behavior for weld-brazed versus brazed-only and welded-only joints. (Reprinted from *Development of the Weld-Braze Joining Process*, T.T. Bales, D.M. Royste, and W.E. Arnold, Jr., NASA Technical Note D-7281, Washington, DC, National Aeronautics and Space Administration, 1973, with permission.)

10.4.5 Hybrid Welding Processes

Just as it is possible to combine two fundamental joining processes to create new, hybrid joining processes (such as weld-bonding), it is possible to combine two different welding processes to create a new *hybrid welding process*. This is usually done to create a hybrid that combines the best characteristics of each parent welding process,

hopefully offering some synergistic benefit(s) as well. Five examples of hybrid welding processes have received some attention, but less use: (1) laser–GTA welding, (2) laser–GMA welding, (3) plasma–GMA welding, (4) plasma–GMA welding, and (5) laser–assisted FSW. These are addressed very briefly in the following paragraphs.

Laser–GTA Welding. The highly monochromatic, collimated, coherent light beam from laser sources permits the surface heat treatment, surface alloying or coating, cutting, drilling, machining, and welding, brazing, or soldering of materials, almost without limit and essentially independent of melting point. One of the principal disadvantages of the laser as a welding heat source is the low efficiency with which the light beam couples to certain materials, as it is caused to reflect rather than be absorbed to cause desired heating. Efficiencies of 10–15% are common, and even lower values prevail for the high conductivity and reflective materials (e.g., aluminum). Reflectivity depends on both inherent optical properties of the materials (e.g., absorption coefficient for certain wavelength radiations) and specularity (i.e., smoothness or polish). Although the majority of weldable metals can be welded by the laser beam process, high thermal conductivity materials like aluminum, copper, and gold are difficult to weld because the surface absorptivity of these materials decreases as their conductivity increases.

The thermal coupling and penetration of a laser can be dramatically enhanced when the laser beam is used with another heat source, an excellent one being an electric arc. When a laser beam source is used with a gas–tungsten arc source the resulting process is called *laser–GTA welding*. When it is done properly, a synergistic effect occurs in which the joint penetration capability of the combined processes is greater than the simple sum of the two individual processes. In addition, the stability of the arc in the GTA process is also markedly improved. To work properly and give rise to these synergistic effects, the laser beam must be placed on axis with a gas–tungsten arc-welding torch. "On axis" means that the laser beam is positioned to within 3.2 mm (1/8 in.) of the tip of the tungsten electrode on a line such that when both processes are operated simultaneously a combined plasma results. This is shown schematically in Figure 10.16. In fact, the gas–tungsten arc can be positioned either above or below the workpiece (as shown in the figure), while the laser impinges upon the workpiece from above. In the first case, the laser and the arc form a combined plasma with stability at low GTAW currents and high rates of travel. When the GTAW torch is placed below the workpiece, the arc preheats the material, increases surface absorptivity, and results in higher process efficiency (i.e., laser coupling) and greater joint penetration for a given laser power level.

Joint penetration is generally 20–50% higher with laser–GTA than with straight GTA welding. Penetration improvements are even more dramatic for higher power lasers. The stability of the arc is also increased, especially at lower currents. Three mechanisms have been proposed to account for these observed phenomena in hybrid laser–GTA welding. The first is stabilization of the anode spot associated with every electric arc. Unlike the normal situation where the motion of the anode spot (located at the workpiece in DC-electrode negative) does not correspond to torch motion, but tends to lag and then snap back under the electrode erratically, in laser–GTA welding the anode spot seems rooted directly under the electrode at all times. This has been

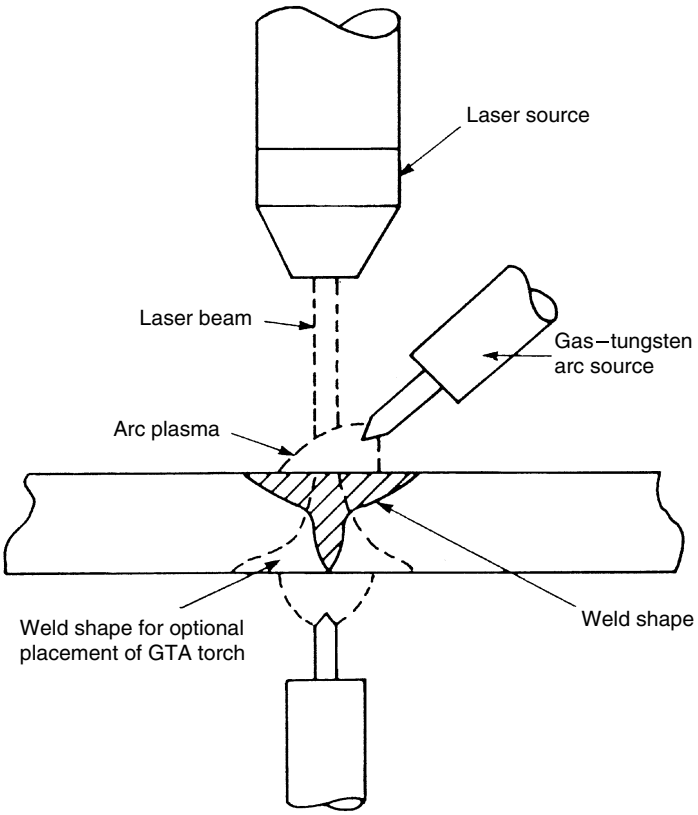

Figure 10.16 Schematic illustration of the hybrid joining process of laser–GTA welding. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 10.11, page 381, Butterworth-Heinemann, Stoneham, MA, with permission of Elsevier Science, Burlington, MA.)

proposed to improve current flow and heating efficiency at the weld. Second, laser-beam absorption is promoted. Laser absorption is improved in the presence of the GTAW arc because the superheated molten region at the surface of the workpiece under the electrode dramatically increases absorptivity. This is true since absorptivity is directly related to the temperature of a body. Third, the direct interaction of photons with gas atoms could be enhancing ionization. The collision of photons with excited gas atoms could be a minor contributor to increased penetration and increased arc stability.

Whatever the precise mechanism or mechanisms involved, the combining of laser beam and GTA welding to create laser–GTAW has interesting and beneficial results.

Laser–GMA Welding. A laser beam source has also been combined with the arc of the gas–metal arc (GMA) welding process in another hybrid process called *laser–GMA welding*. The mechanism or mechanisms leading to improved arc stability and increased penetration in laser–GTA welding operate in laser–GMA welding to also

increase arc stability, especially at low currents, and increase molten metal deposition rate by the laser, helping to melt the consumable wire electrode of the GMA process. This process has been used for both applying welded surface layers and for "shape welding." In shape welding, actual three-dimensional shapes are produced by building up weld metal into a mold or over a form. The novelty with laser–GMA welding, enabled by the superb control of the combined arc and laser beam energy, is the ability to produce such shapes "freeform" (i.e., without any mold). To work, the GMAW source is computer-controlled to deposit layer upon layer of weld metal to create the desired 3-D shape from stacked 2-D slices. Figure 10.17 shows a 3-D part made by such a laser-assisted hybrid welding process in which a controlled powder additive is applied, even to allow the creation of functionally gradient material parts.

Plasma-Laser Welding. Transferred arc plasma arc welding sources have also been used successfully to produce 3-D shapes layer by layer (as in laser–GMA welding

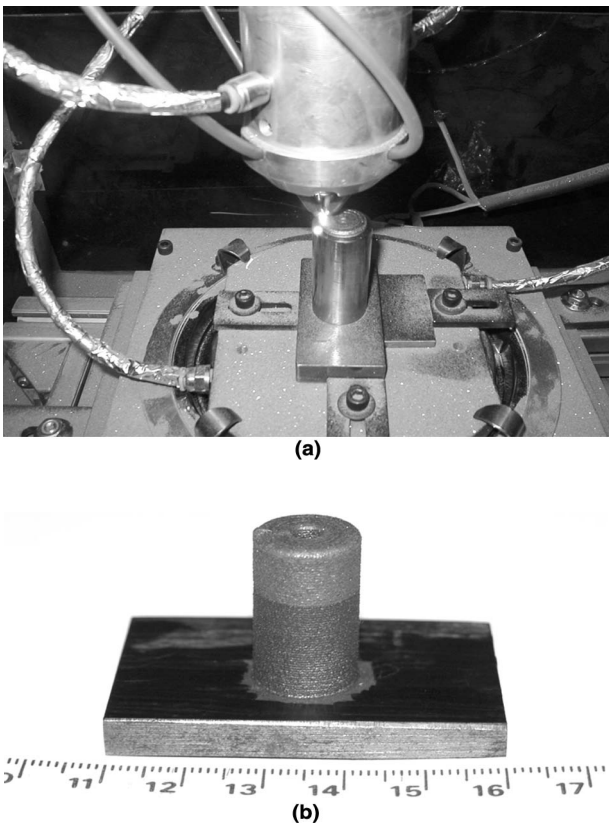

Figure 10.17 A photograph showing the laser-assisted arc or plasma welding deposition of coatings from powders (a), which allows parts to be produced that are functionally gradient materials in both axial and radial directions (b). (Courtesy of the Advanced Manufacturing Research Center at Southern Methodist University, Richardson, TX, with permission.)

above), with filler wire being fed into the combined laser-enhanced plasma using computer control coupled to torch control to trace each 2-D layer. The hybrid process of plasma–laser welding, while offering superb deposition control (largely through enhanced plasma stability), could also be used to provide increased joint penetration.

Plasma–GMA Welding. In 1972, engineers at Philips Research Laboratories in Einhoven, The Netherlands, developed an electrode holder that combines the features of plasma arc and gas–metal arc welding (see Figure 10.18). When operated at certain power levels, the system produces welds that differ from those of either of the component processes used separately. The resulting *plasma–GMA welding* process is, thus, another hybrid welding process. For plasma generation, an inert gas (e.g., argon) is used, while either argon or carbon dioxide can be used for shielding. The resulting plasma arc is of the transferred type, the workpiece being connected on the negative side of the circuit.

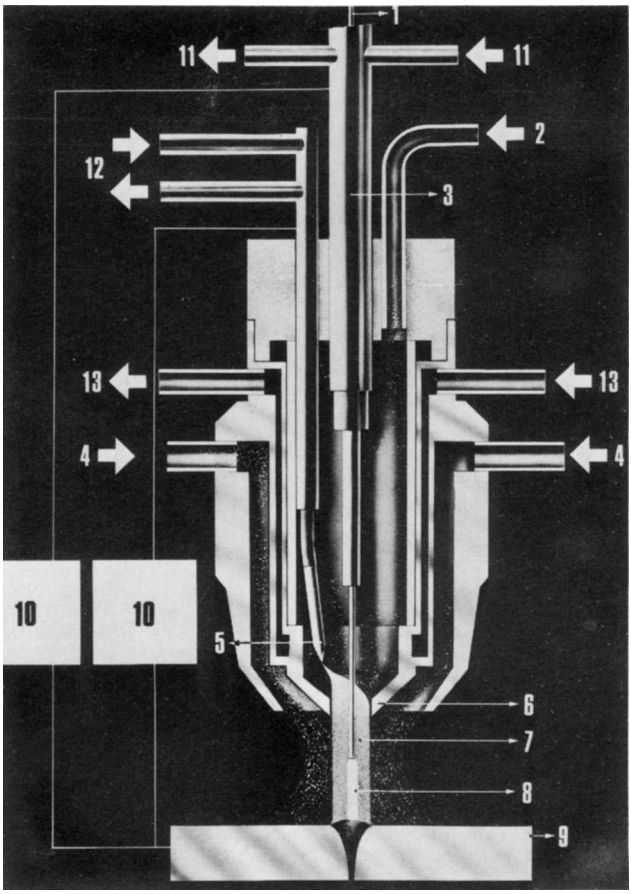

Figure 10.18 Schematic of a plasma–GMA welding torch. (Reprinted from "A new process: Plasma–GMA welding," Philips Research Laboratories, Einhoven, The Netherlands, *Welding Journal*, 51(8):56, 1973, with permission of the American Welding Society, Miami, FL.)

In operation, the gas-metal arc electrode is fed through the center of the shielded plasma stream. Under DCRP (electrode positive), the filler metal consumable electrode establishes its own arc while being preheated by the surrounding plasma arc. Under these conditions, two modes of operation have been discovered that have widely different metal deposition characteristics. First, when comparatively low currents are passed through the consumable electrode, a firm narrow arc is established. This is good for high-speed welding of thin sheet or deep penetration of plates. Second, when the current in the filler metal rises above a certain transition value, the mode of deposition changes, with swirling of the electrode arc in the plasma producing a shower of fine drops. A flat, shallow penetration results, with very low heat input.

Laser-Assisted Friction Stir Welding (FSW). The friction stir welding (FSW) process was described in Subsection 6.5.3 as employing a rapidly rotating pin while it is squeezed between the abutting edges of two pieces of metal. The resulting frictional force literally stirs metal in the solid (but plastic) state to create a weld. Depending on the metals involved and the thickness of the pieces being welded, the forces generated and the power required can be high. Recent work at Southern Methodist University's Advanced Manufacturing Research Center has combined a Nd:YAG laser with FSW to preheat the metal ahead of the rotating pin, thereby lowering the flow strength of the metals and reducing the forces involved and the power required. Figure 10.19 shows the laser-assisted FSW process in operation.

Table 10.5 lists current hybrid welding processes and their alleged advantages.

10.5 OTHER COMBINATIONS: WHAT MAKES SENSE AND WHAT DOES NOT?

The combinations of welding with adhesive bonding in weld-bonding and with brazing in weld-brazing, and of riveting with adhesive bonding in rivet-bonding, were all described as interesting hybrid joining processes. But the possibilities other useful hybrids by combining fundamental as well as specific process embodiments (e.g., resistance spot weld-bonding versus laser beam spot weld-bonding, or laser beam welding with gas–tungsten arc welding) seem endless. The question is, are they endless? Some combinations make sense in that the combination offsets weaknesses of one process with the strengths of another, and the possibility exists that there could be some synergistic effect. Other combinations, on the other hand, do not make sense in that strengths and weaknesses of the two parents not only do not offset one another, but the weaknesses add in the worst case, and absolutely no advantage is gained in other cases (despite almost inevitable higher cost). It is always important to consider whether certain combinations make sense or not.

Perhaps the best example of a bad joining combination is the combination of welding (especially continuous welding) and bolting. It was actually engendered by misinterpretation of an old adage attributed to conservative engineers, viz., "To be safe, use belts and suspenders." The origin of the adage, of course, is sound—if one wears both a belt and suspenders the likelihood of losing one's pants goes to near zero.

Figure 10.19 A laser-assisted friction stir welding system in operation. (Courtesy of the Advanced Manufacturing Research Center at Southern Methodist University, Richardson, TX, with permission.)

Table 10.5 List of Hybrid Welding Processes and Their Advantages

Laser–GTA Welding
- Dramatically enhanced laser coupling versus LBW alone
- Increased GTAW penetration
- Improved arc (especially low current) stability for the GTAW process

Laser–GMA Welding
- Increased arc (especially low current) stability for the GMAW process
- Increased molten metal deposition rate versus GMAW alone
- 3-D shape welding is practical into molds

Plasma–Laser Welding
- Enhanced plasma stability
- Superb metal deposition control
- 3-D shape welding is practical into molds or freeform

Plasma–GMA Welding
- At low currents, a fine, narrow arc allows higher welding speed in sheet gauges or deeper penetration in plate gauges
- At higher currents (above some transition value), molten metal deposition occurs with a swirling arc to produce a flat, shallow deposit with very low heat input

Laser–Assisted Friction Stir Welding (FSW)
- Reduced power required to operate the friction stir welding tool tip
- Increased tool tip life
- Improved stirring action

However, when this sound philosophy concerning pants is applied to joining of heavy structure, it proves false. As an example, it is not at all uncommon for companies to repair expensive or irreplaceable cast-iron frames on large machines (such as forging presses) by first gouging out the crack that led to failure, and preparing a proper groove to be filled by fusion welding using a 100% Ni or 55Ni–45Fe filler or even braze welding with a Ni–Cu alloy or bronze. Then, after a sound, full-penetration, continuous weld has been made, a "splice plate" is added for good measure. This involves positioning heavy steel plates (often one on opposite sides of the failed frame member), drilling holes through the plates and the frame on each side (but away from) the newly made weld, and inserting high-strength bolts. This approach, like belts and suspenders, provides only redundancy—no synergy. If the weld holds, the bolts do not carry any load when the frame is stressed. The point is, either the belt holds up one's pants at any given moment, or the suspenders do. They both do not do it!

In conclusion, with all the many embodiments of mechanical fastening, integral mechanical attachment, adhesive bonding, fusion and non-fusion welding, brazing, and soldering, the likelihood of needing a hybrid process is low. But if an occasion seems to arise for a new hybrid process to be developed, or the benefits found to arise from two processes being combined seem to be real, then pursuit, development, and application of the hybrid process is worthwhile. If all that is being sought is redundancy of joining for an added measure of safety and security, that is all right, but nothing more should be attributed to what has been achieved than that.

SUMMARY

It is possible to modify or combine the fundamental approaches of mechanical joining, adhesive bonding, and welding (including brazing and soldering) to create useful variants and even hybrids. *Variants* are different, often subtly different, ways of using a basic process to accomplish joining; sometimes their effects appear to be quite unique, and at other times their effects seem almost indistinguishable from the original process. *Thermal spraying* is an example of a variant process that appears quite unique, while *braze welding* is an example of a variant process that seems almost indistinguishable from normal gas or arc welding. *Hybrid processes* are entirely new processes, derived from the combination of two other (parent) processes. Not only does the resulting hybrid provide new capability, it often (and ideally) does so through some synergistic effect in which the strength of one parent process offsets the other's weakness. The resulting totally new capability is clearly more than simply the addition of the capabilities of the two parent processes. Examples of hybrid joining processes are *rivet-bonding, weld-bonding,* and *weld-brazing*.

Thermal spraying applies material as molten or simply softened (i.e., plastic) particles created by heating a particulate or powdered feed material, or melting and "atomizing" a continuous solid wire or discontinuous rod and propelling those particles at high velocity so they strike a substrate and flatten, stick, and build up. Bonding between the particles and the substrate by adhesion (and between particles within the deposit by cohesion) involves atomic-level bond formation, with a degree of interdiffu-

sion and/or chemical reaction, as well as some mechanical interlocking of particles with the "nooks and crannies" on the substrate or on one another. Methods for heating and propelling material include (1) flame (or combustion) spaying, (2) electric arc spraying, (3) non-transferred plasma arc spraying, and (4) detonation flame spraying. The strength of adhesion and cohesion, and the density of the deposited coating, depend directly on the homologous temperature and kinetic energy of the particles during spraying. The process can be used to create free shapes, create shapes in or over forms, restore lost material and dimensions, apply protective or decorative coatings, produce joints (by applying braze filler or thermoplastic adhesive to be fused following spraying), or consolidate reinforcements into matrix materials to make composites or create other special microstructures.

Braze welding enables the joining and, especially, repair of heat-sensitive materials such as cast iron. It does so by filling a groove with a filler alloy that melts below the solidus of the base material(s), so no substrate melting occurs (as in brazing). However, capillary action is not used to distribute the filler.

Rivet-bonding, weld-bonding, and weld-brazing all improve out-of-plane (i.e., peel) strength of the adhesive or braze. They also all extend the service temperature range of the adhesive of braze for in-plane shear loads. Rivet-bonding and weld-bonding also dramatically improve resistance to fatigue by the adhesive's softening the concentration of stress at fasteners or welds, and they improve energy absorption or crashworthiness and reduce vibration through damping.

In addition to combining the various basic joining processes to create hybrids, it is possible to combine specific welding processes to create *hybrid welding processes*. Five examples are laser–GTA, laser–GMA, plasma–laser, plasma–GMA, and laser-assisted FSW. These all offer some interesting capabilities, including improved deposition rates with exceptional control of contour, improved penetration with minimal increase in net heat input, greater arc stability, and others.

Not every combination of basic or even specific joining processes makes sense, in that the strengths and weaknesses of parent processes may not offset each other, and weaknesses might even add. Care must be taken in deciding if new combinations are worthwhile for more than simple but valuable redundancy.

QUESTIONS AND PROBLEMS

1. Differentiate between special joining processes that are variations (or variants) of the fundamental processes of mechanical fastening, adhesive bonding, and welding (including brazing and soldering) and processes that are hybrids of these. Cite two examples of each, and explain what makes each a "variant" or a "hybrid."
2. How does the process of thermal spraying operate? How is thermal spraying a variant of fusion welding? How might it be considered a variant of brazing? How might it be considered a variant of adhesive bonding?
3. There are four major process embodiments of thermal spraying. Briefly describe how each operates, emphasizing differences. Rank-order these four variations in

terms of heat source intensity and in terms of particle velocity. What is the importance of heat source intensity in coating application? What is the importance of particle velocity?

4. What are five different applications of thermal spraying, and why is thermal spraying a particularly viable process?
5. Differentiate among braze welding, fusion welding, and brazing. Give some advantages of braze welding.
6. Describe the process of rivet-bonding. What are the advantages of this hybrid over the two parent processes? Give two examples of where this hybrid joining process would make sense.
7. Describe the process of weld-bonding. What are the advantages of this hybrid over the two parent processes? Give two examples of where this hybrid joining process would make sense.
8. Describe the process of weld-brazing. What are the advantages of this hybrid over the two parent processes? Give two examples of where this hybrid joining process would make sense.
9. Describe two major hybrid welding processes, giving the synergistic attribute of each.
10. How might hybrid welding processes' potential for producing freeform 3-D shapes prove useful in industry?

Bonus Problem:

A. One of the toughest things to prove for a hybrid process, such as weld-bonding, is that fatigue strength (or life) is benefited synergistically. How would you prove this?

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PART II

Joining of Specific Materials and Structures

Chapter 11

Joining of Metals, Alloys, and Intermetallics

11.1 INTRODUCTION

11.1.1 Challenges of Joining Metals and Alloys

In many ways pure metals and their alloys, as a generic group, are the easiest of all materials to join. Of course, there are exceptions for certain extreme types of metals or alloys, but even these can be easily joined compared to most other materials (e.g., ceramics, glasses, polymers, and, certainly, reinforced composites). Mechanical methods employing threaded and unthreaded fasteners, integral mechanical attachment methods (relying on rigid, elastic, and plastic features), adhesive bonding, fusion and non-fusion welding, brazing and soldering, braze welding, thermal spraying, and hybrid rivet-bonding, weld-bonding, and weld-brazing can all be used for many different metals and alloys, in many different combinations.

The reason for this relative ease of joining comes about from the inherent nature of metals. Unless special effort is taken to cause it to be otherwise, metals are solids comprised of regular three-dimensional arrays of atoms having long-range order (i.e., they are crystalline).[1] For virtually all metallic elements, of which there are about 72 (excluding the elements above atomic number 92, the transuranic elements) in the periodic table, atoms aggregate by surrounding themselves with as many other atoms of their kind as possible based solely on their size as approximate spheres. Atoms are held together by bonds that result as each atom in the aggregate shares its outermost electrons with all other atoms in its vicinity, causing each atom to attain a stable electron configuration and lowest potential energy state through this extended sharing. An alternative view of this situation is that the positive ion cores of atoms (consisting of the atom's nucleus and all but its outermost shell of electrons) are held together by the permeating "sea" or "cloud" of outermost or valence negative electrons. The resulting "metallic bonding" gives solid metals their inherent properties, which

[1] By employing extremely fast cooling rates (typically exceeding $10^{6\circ}$ K/second), atoms in a molten metal can be prevented from taking up a long-range ordered array in the solid state, forming an amorphous metal or metal glass. For certain complex combinations of metallic elements, some alloys can be caused to remain in the glassy state with considerably slower, but still quite rapid-cooling rates (e.g., $10^{4-}10^{5\circ}$ K/second).

include (1) typically high cohesive strength; (2) high stiffness due to the strength of the metallic bonds; (3) ability to respond to an imposed shear stress by having one layer of atoms slip over another without leading to cohesive failure by fracture (that is, they exhibit good ductility and toughness); (4) good electrical conductivity; and (5) thermal conductivity.

Metallic bonding and the inherent properties that result also explain why metals are so easy to join. Metals are strong enough (particularly at room temperature, or below about 0.4 $T_{abs.MP}$) to sustain even point loading without yielding. At the same time, they are also ductile enough and tough enough to tolerate stress concentrations better than brittle materials. They can absorb mechanical work without fracturing, thus allowing them to be drilled to accept unthreaded fasteners, tapped to accept threaded fasteners, or machined to create rigid integral attachment features. They are inherently elastic enough (because of the springiness of their bonds) to allow the operation of elastic integral attachment features, and plastic enough (because they can be made to deform without fracturing) to allow the creation of plastic integral attachment features. The habit of metal atoms to try to surround themselves with as many other metal atoms as possible means new metal can be easily added to existing metal by the generic process of welding, the subprocesses of brazing and soldering, and the variants of braze welding and thermal spraying, including between different elemental species or between alloys. The tendency of metals to undergo chemical reactions involving oxidation is one reason they can be joined by adhesives; other reasons are the presence of surface layers that facilitate adsorption, and lattice structures that facilitate diffusion.

This chapter looks at the joining of these interesting and diverse materials. The ease with which metals can be joined will not be fully appreciated until the difficulties encountered in attempting to join other materials are seen in subsequent chapters.

11.1.2 Special Challenges of Joining Metals and Alloys

The special challenges of joining pure metals and metallic alloys to one another are largely associated with extremes.[2] Joining of metals and alloys with extreme melting temperatures, extreme reactivity, particular sensitivity to heat, highly incompatible chemical or physical properties, extremes of geometry, or extremes of environment in which they must be joined and/or survive all present special challenges.

Refractory metals and alloys (e.g., tungsten, molybdenum, tantalum, hafnium, and others) can be difficult to join because of their extremely high melting and use temperatures. Melting by most fusion-welding processes can be difficult or impossible. Susceptibility to embrittlement from contamination by oxygen, hydrogen, or other interstitials is high. Suitability to extreme elevated temperatures limits the utility of brazing and normally precludes soldering and adhesive bonding. The body-centered cubic crystal structure of the refractory metals and their most common alloys leads to a

[2] In fact, all joining is made more difficult by extremes in the structure and/or properties of the materials to be joined, as such extremes almost inevitably lead to incompatibilities.

ductile-to-brittle transition at relatively high temperatures compared to other metals, and grain growth at extreme elevated temperatures can be severe, leading to loss of ductility and toughness.

Reactive metals and their alloys (e.g., titanium, zirconium, niobium,[3] beryllium, and others) are challenging to join by welding, brazing, and soldering because of their extreme reactivity. These metals tend to form tenacious oxides, which, in turn, impede wetting. They also tend to form brittle compounds (e.g., carbides, nitrides, hydrides) during welding or intermetallics (e.g., with Cu, Sn, In, etc.) during brazing or soldering that can degrade performance in service, especially under fatigue or impact loading.

Many metal alloys are very sensitive to heat input. Low-melting metals and alloys (such as aluminum, magnesium, tin, lead, and zinc), age-hardenable alloys (such as heat-treatable aluminum alloys and nickel-based superalloys), transformation-hardened (e.g., quenched and tempered steels) or transformation-hardenable alloys (such as medium or high carbon and low alloy and tool steels), and inherently brittle alloys (such as cast iron) are all extremely prone to thermal damage (e.g., cracking) or property degradation (e.g., softening or embrittlement) by welding.

Dissimilar metals and alloys can be incompatible in terms of their chemical and/or physical properties, leading to the formation of embrittling phases or the development of deleterious internal stresses. Chemical incompatibility can severely limit mutual solubility and can frequently cause embrittlement through the formation of intermetallic compounds at interfaces (e.g., copper to austenitic stainless steel or tin-based solders to copper). The problem of incompatibility is again most serious when extremes are involved, such as extreme differences in chemical properties (e.g., electronegativity or mutual solubility), physical properties (e.g., melting temperatures or coefficients of thermal expansion), or even mechanical properties (e.g., strengths or elastic moduli).

Sometimes the extremes that cause difficulty in joining are not just due to the material's nature but are related to the geometry of the assembly or to the joining or service environment. Examples include (1) joining of very thin sections, (2) joining of very thick sections, (3) joining of very small components, (4) joining of very large components, and (5) joining in hostile environments such as outer space, underwater, or areas of high radioactivity. These structural and environmental challenges to joining will be addressed in Chapter 16, Sections 16.2 and 16.3.

11.1.3 Challenges of Joining Intermetallics

Joining of intermetallic compounds or long-range-ordered (LRO) alloys, in both monolithic[4] and composite forms, is important as these materials are increasingly considered for applications in environments of severe temperature and corrosiveness. Aluminides, silicides, and borides of Fe, Ni, Ti, and refractory metals (e.g., Mo, Hf, and

[3] Niobium (Nb) was once known as and, in some places around the world, is still called "columbium" (Cb).
[4] In materials science, the term "monolithic" refers to materials that are elastically continuous and chemically homogeneous, as opposed to being composed of different materials or multiple pieces.

Nb) are the subject of extensive interest and development. As a group, intermetallics tend to be brittle and refractory, making joining (especially by welding) a challenge. Many of these materials derive their unique and attractive elevated temperature properties (e.g., increased strength with increased temperature) from the fact that they exhibit long-range ordering. Welding can disrupt this order and, thus, undermine this desirable characteristic.

The following sections will address the joining of metals, alloys, and intermetallics.

11.1.4 Joining Process Options for Metals and Alloys

Metals are used in structural applications more than most other materials, so joining of metals and their alloys is an extremely important process in fabrication, construction, and assembly. Much of the popularity of metals is related to their general high strength, ductility, toughness, and fabricability, including castability, formability, and machineability. Other desirable characteristics are electrical and thermal conductivity, resistance to many corrosive environments, and, for many metals, serviceability at elevated temperatures. The predominant method for joining metals and alloys is welding, which includes the subcategories of brazing and soldering, but essentially all other methods of joining (including mechanical fastening and integral attachment, adhesive bonding, braze welding, thermal spraying, rivet-bonding, weld-bonding, and weld-brazing) are possible and are used.

Figure 11.1 shows a steel-hulled ship under construction using welding to join structural elements.

The reason for the popularity of welding, brazing, and soldering is that these processes result in strong joints through the creation of primary atomic (i.e., metallic) bonds. Metals readily form metallic bonds with other metals, as long as intimate contact is achieved between clean faying surfaces. For this reason, joining under the action of heat and/or pressure is relatively easy and the resulting joints are sound. Resulting structural integrity is high, structural efficiency (i.e., strength-to-weight ratios) and joint efficiency (i.e., joint-to-base-material stress level ratios) are generally high, and physical properties such as electrical or thermal conductivity are essentially unaffected by the joining process or the joint. Continuous welds also provide excellent hermeticity and, if done properly, provide superb environmental durability.

Also popular as joining methods for metals and alloys are mechanical fastening and integral mechanical attachment. Here, the good ductility and fabricability of most metals and alloys permit the use of fasteners, since required fastener holes can be produced easily. Likewise, designed-in and processed-in (including formed-in) rigid, elastic, or plastic integral attachment features can also be produced easily. The toughness of metals, combined with their high strength, can tolerate the stresses associated with hole production and fastener installation and the stress concentrations associated with holes or integral attachment features developed under service loads. Ease of disassembly is a major benefit of mechanical joining, as is the inherent damage tolerance of the structural assembly afforded by physical barriers (e.g., joint faying

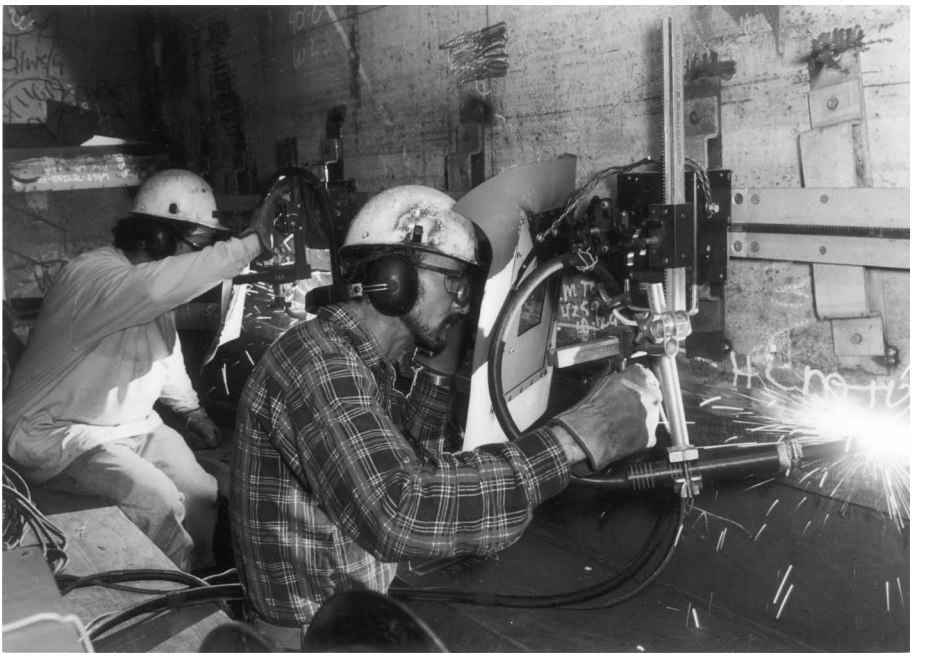

Figure 11.1 Fusion arc welding is the predominant joining process used in the construction of a metal (e.g., steel, aluminum alloy, titanium alloy) ship. Large parts are joined to produce sub-assemblies, sub-assemblies are joined to produce modules, and modules are joined to create the ship. Here, welding operators employ a mounted track to accurately control welding speed, arc length (and, thus, voltage), etc. (Courtesy of Northrop Grumman's Newport News Shipbuilding, Newport News, VA, with permission.)

surfaces) preventing crack propagation out of one structural member into another. The shortcomings of mechanical fastening compared to welding are principally lower structural efficiency (i.e., joint strength to weight), and possible loosening and leaking.

Adhesive bonding is less popular, but is feasible and is being used more often for metallic joining. Load-carrying capacity can be quite high using large bonding areas, and damping characteristics can be excellent in metals, which tend to have the inherent property of transmitting elastic waves such as vibrations (i.e., they have low damping coefficients). Structural integrity can be high, but structural efficiency (i.e., strength to weight) and joint efficiency for some applications (e.g., bonding thick sections) can be quite limited. The single greatest shortcoming is that environmental durability can be a problem if temperatures are high or very low, or if there is prolonged exposure to water, humidity, solvents, weather, and so on.

Thermal spraying of metals onto similar or dissimilar metals, onto ceramics, or even onto polymers works well, producing adherent coatings when done properly. Most hybrid joining processes can be used, often to special advantage.

Table 11.1 list the various options for joining metals and their alloys, as well as for joining intermetallics.

Table 11.1 Options for Joining Metallic and Intermetallic Materials (in approximate descending order of popularity)

Fusion Welding*
Mechanical Fastening*
-Bolting
-Riveting
Non-Fusion Welding*
Brazing*
Soldering (especially for electrical applications)
Adhesive Bonding (especially for thin gauges)*
Integral Mechanical Attachment (especially tab folding methods in thin sheet gauges)
Thermal Spraying*
-Oxy-Fuel Gas (Combustion) Flame Spraying
-Plasma Spraying
-Electric Arc Spraying
-Detonation Flame Spraying
Weld-Bonding
Rivet-Bonding
Weld-Brazing

*Most popular with intermetallic materials, in approximate descending order: Fusion welding, non-fusion welding, brazing, mechanical fastening, thermal spraying, adhesive bonding.

11.1.5 Dealing with Extremes

As we have seen, metals and their alloys are generally easy to join by a wide array of general and specific processes. Challenges to joining tend to come about when extreme material properties, extreme structural situations, or extreme service environments are involved. In the next several sections, the challenges posed by the most prevalent extreme material properties are addressed, while in Chapter 16, Sections 16.2 and 16.3, the challenges associated with the most extreme structural and environmental conditions are addressed. Chapter 15 deals with the challenges associated with joining dissimilar materials, which itself can constitute an extreme condition.

11.2 JOINING REFRACTORY METALS AND ALLOYS

11.2.1 Challenges Posed by Refractory Metals and Alloys

Refractory metals and metallic alloys are those that have very high melting points and, thus, can function and survive in high-temperature environments. In decreasing order of melting point, the most common refractory metals by far are tungsten (W), tantalum (Ta), molybdenum (Mo), and niobium (Nb). Others (also in decreasing order of melting point) include rhenium (Re), osmium (Os), ruthenium (Ru), iridium (Ir), and hafnium (Hf). All melt over 4,000°F (2,205°C), which has been taken by most practitioners (albeit somewhat arbitrarily) to be the threshold of refractoriness. Other metals and

their alloys are also sometimes considered refractory, as they melt over 3,000°F (1,650°C); they include (in decreasing order of melting point) rhodium (Rh), chromium (Cr), and vanadium (V). Table 11.2 lists the refractory metallic elements (i.e., metals) and some of their most common and important alloys, along with their melting temperatures or ranges, and various useful properties for elevated-temperature service. It should not come as too much of a surprise that there are really relatively few actual alloys based on refractory metals, especially W and Mo, because conventional melt-metallurgy is so difficult to employ. Options for supplying needed heat and reaching required temperatures are limited to electric arcs, plasmas, or electron or laser beams.

As a group, these metals have body-centered cubic (bcc) crystal structures, high to very high densities, low specific heats, and low coefficients of thermal expansion. Mechanical strength and retention of strength at elevated temperatures are excellent. Like most BCC metals, the refractory metals exhibit a ductile-to-brittle transition in their impact behavior, often at surprisingly low temperatures compared to their high melting temperatures (see Table 11.2).

The high melting temperature of these metals and their alloys makes casting difficult, impossible, or impractical, and deformation processing can be difficult because of their BCC structures and high working temperatures. Most refractory metals and alloys are thus produced by powder metallurgical techniques, viz., billets are produced from refined metals, the billets are atomized into powders, and the powders are pressed and sintered into net-shaped parts. Another possible production method involves arc, plasma, laser beam, and electron beam melted and cast forms, which represent expensive melt processing. Really complex structural forms and parts from refractory metals and alloys are typically obtained by hot compacting and sintering, hot isostatic pressing, or, more recently, powder injection molding. However, large and/or complex-shaped structures frequently require joining because of net-shape processing limitations.

As a result of the methods of metal and alloy production, defect content (e.g., porosity) and contamination (e.g., absorbed gases or oxide or other inclusion) levels can be high. Working to create the desired finished shape is usually done while warm rather than hot (not much above the recrystallization temperature) to prevent excessive grain growth and attendant loss of ductility. The result of all of this is that the final microstructure can be quite heterogeneous, further complicating processing (by forming or machining) and welding.

Refractory metals and their alloys tend to be susceptible to contamination by elements that go into interstitial solid solution, especially oxygen, nitrogen, carbon, and sometimes hydrogen (e.g., in Ta and Nb), during processing and in service. As a result, contamination must be avoided by excluding these elements during processing (including joining) and through the use of coatings for sustained elevated temperature service.

Since these materials tend to be selected and used for their refractoriness, joining options are usually limited to those methods that produce joints that can tolerate elevated temperatures. Mechanical fastening and integral mechanical attachment, welding, and brazing (using special fillers that are, themselves, refractory) tend to be the methods of choice. While possible, soldering and adhesive bonding are generally not viable since the service temperatures for which the refractory metals are usually selected in the first place are probably too high for the joints made by these processes to

Table 11.2 Refractory Metals and Their Most Common Alloys

Metal or Alloy	*Melting Point °C(°F)*	*Density at 20°C g/cm³*	*Recrystallization Temp. °C(°F)*	*Ductile-Brittle Transition Temp. °C(°F)*	*Elastic Modulus GPa (10^6psi)*	*CTE. at 20°C 10^{-6} °C^{-1}(°F^{-1})*
Tungsten (W)	3,390 (6,130)	19.3	1,200–1,650 (2,190–3,000)	260–370 (500–700)	345 (50)	4.5 (2.5)
3Re–W						
25Re–W						
Tantalum (Ta)	2,996 (5,425)	16.6	1,100–1,400 (2,010–2,550)	< −195 (< −320)	189 (27)	6.5 (3.6)
2.5W–Ta (KBI-10)						
10.0W–Ta (Ta–10W)						
2.5W–0.15Nb–Ta (PS–63)						
8W–2Hf–Ta (T–111)						
10W–2.5Hf–0.01C–Ta (T–222)						
8W–1Re–0.7Hf– 0.025C– Ta (Astar 811C)						
Molybdenum (Mo)	2,620 (4,750)	10.2	1,150–1,200 (2,100–2,190)	150–260 (300–500)	324 (47)	4.8 (2.7)
0.5Ti–0.08Zr–Mo (TZM)						
5Re–Mo						
30Re–Mo						
Niobium (Nb)	2,468 (4,474)	8.57	985–1,150 (1,805–2,100)	−200-−75 (−320-−105)	105 (15)	7.1 (3.95)
1Zr–Nb (Nb–1Zr)						
5Mo–5V–1Zr–Nb (B–66)						
10Hf–1Ti–Nb (C–103)						
10W–1Hf–0.1Y–Nb (C–129Y)						
10W–2.5Zr–Nb (Nb–752)						

28Ta–11W–2.5Zr–Nb (PS–85)						
10Ta–10W–Nb (SN 6–29)						
Other Refractory Metals:						
Rhenium (Re)	3,167	20.53	-	-	465	12.45(6.9) //c-axis
	(5,732)				(66.7)	4.67(2.6) ⊥ c-axis
Osmium (Os)	~2,700	22.5	-	-	565	6.0
	(~4,900)				(81.0)	(3.33)
Ruthenium (Ru)	~2,500	12.2	-	-	418	9.6
	(~4,532)				(60.0)	(5.3)
Iridium (Ir)	2,454	22.4	-	-	530	6.5
	(4,459)				(76.0)	(3.6)
Hafnium (Hf)	2,230	4.5	-	-	138	5.9
	(4,046)				(19.8)	(3.27)
Rhodium (Rh)	1,966	12.4	-	-	296	8.5
	(3,560)				(42.5)	(4.72)
Chromium (Cr)	1,920	7.1	-	-	251	8.2
	(3,490)				(36.0)	(4.56)
Vanadium (V)	1,700	5.96	-	-	132	8.3
	(3,092)				(19.0)	(4.61)

provide useful properties. Some adhesive bonding is performed with refractory metals and alloys, but usually for joining to ceramics using inorganic refractory ceramic cements (see Chapter 15, Section 15.3 and Subsection 15.6.3).

11.2.2 Mechanically Joining the Refractory Metals and Alloys

Refractory metals and their alloys can readily be joined by mechanical methods, using either fasteners or integral attachment features (i.e., interlocks). General methods are typical of those described in Chapter 3, Sections 3.3, 3.4, and 3.5, but often with special modifications for the severe thermal environment for which refractory materials are most often selected. The key considerations in mechanical joining of refractory metals and alloys are thermal in origin, including differential expansion and contraction, thermal fatigue, and microstructural thermal stability. These problems arise from the fact that refractory materials are generally used at high service temperatures, so the severity of thermal excursions gives rise to considerable changes in the dimensions of and fit between structural components and can cause degrading reactions and metallurgical changes. The relatively low coefficients of thermal expansion for the refractory metals and alloys mean that mismatch with other metals and alloys is likely. The CTEs of the fastener material and the refractory base metal or alloy joint members should match as closely as possible, ideally (and as a rule) being no more than 15% different. For the best compatibility, chemically and physically, refractory metal or alloy fasteners should be used with like refractory metal or alloy joint elements. Thermally induced stresses can be minimized by using fastener, fastener hole, and integral attachment feature designs that allow limited relative movement of the joint elements during thermal excursions. These so-called ''slip-joints'' can use loose-fitting fasteners, slots rather than round holes, etc. Some examples of such joints are shown schematically in Figure 11.2.

Thermal stability of the joint elements and the fasteners, provided they are both made from suitable refractory metals or alloys, is usually dealt with by employing appropriate thermal barrier coatings to prevent oxidation or other adverse chemical reactions or unwanted diffusion. Obviously, one of the problems encountered when trying to use fasteners that operate by developing a clamping force through preload (e.g., bolts) is that the preload in the fastener is lost by yielding or other thermally activated stress relaxation mechanisms.

11.2.3 Welding the Refractory Metals and Alloys

Refractory metals and alloys can be welded using either fusion or non-fusion welding processes, provided the fusion processes have sufficient melting power and the non-fusion processes can handle the needed shapes. Two keys to successfully welding the refractory metals and their alloys are achieving melting (for fusion welding) or softening (for non-fusion welding) for coalescence and preventing embrittlement from absorbed interstitial solutes. For fusion welding, the high energy density processes are generally more successful, as they are better able to cause melting. Electron beam, laser beam,

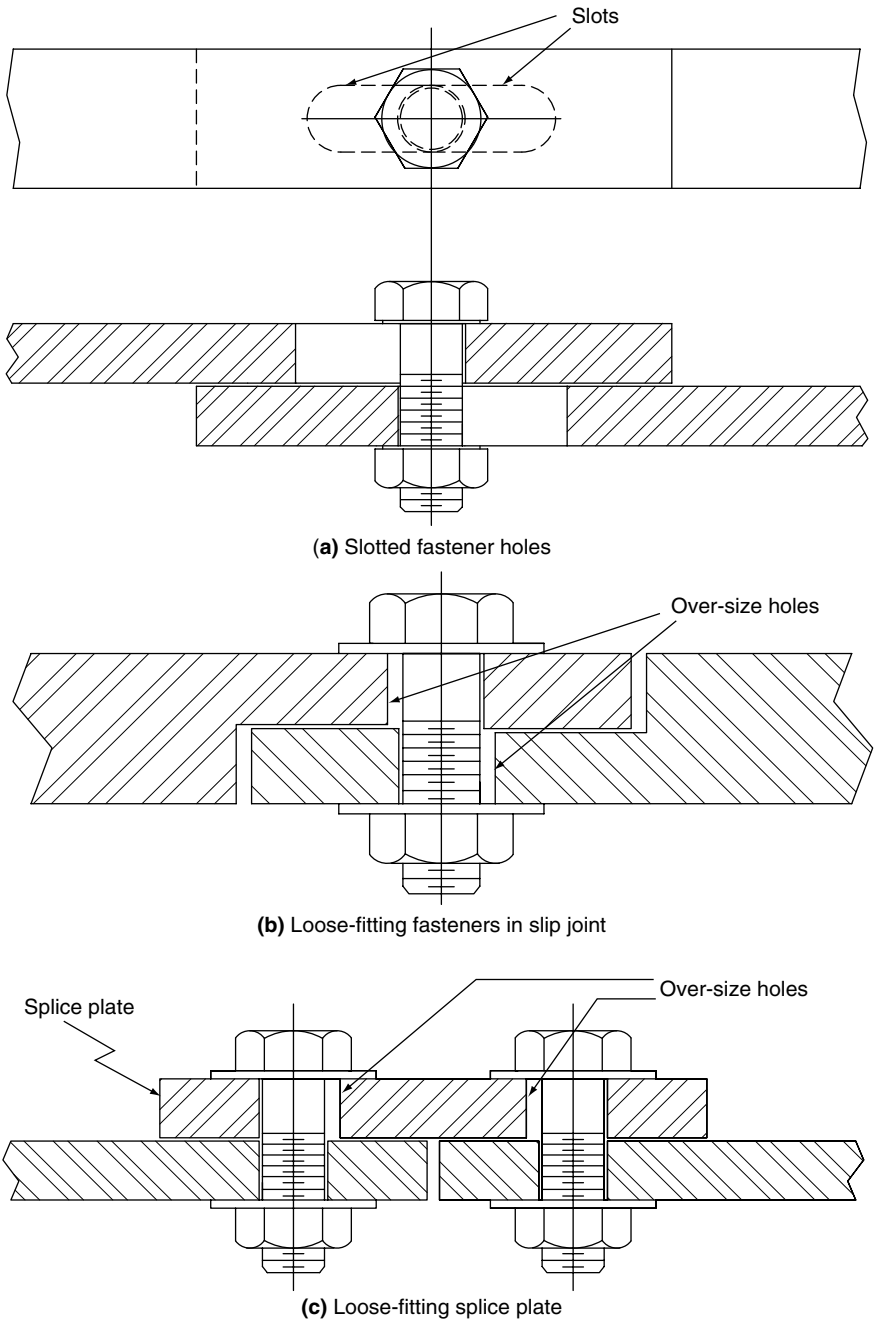

Figure 11.2 Schematic illustration of special techniques for mechanically joining refractory metals and alloys, including slotted fastener holes (a), loose-fitting fasteners in slip joints (b), and loose-fitting splice plates (c).

and plasma arc welding processes are commonly used, but so is gas–tungsten arc welding. Welding can be and often is accomplished autogenously, but fillers, usually of closely matched composition to the base materials, can also be used. For electron beam welding, protection from contamination is provided by the vacuum employed with the beam. For the other processes, inert shielding gases (e.g., argon or helium) are used, with special care to ensure that the welding environment and shielding gas are dry. Resistance welding (RW) processes offer another viable alternative to the high energy density processes, as there is virtually no limit to the melting power provided by IR^2 heating. The sheer speed of many resistance welding processes, together with the degree of self-protection from oxidation afforded by tight-fitting lap joints, usually are sufficient to prevent contamination. Spot, projection, seam, and percussion embodiments of RW are used with success.

The problem of obtaining melting can be overcome by using non-fusion processes. Usually, the heat generated by friction or explosion welding are sufficient to cause coalescence between mating joint elements. Pressure welding, using forging or pressing, is generally not able to produce quality welds, but can be used with special attention to process setup and control. Solid state diffusion welding is definitely possible, although diffusion temperatures have to be high (typically over 0.7 $T_{\text{absolute MP}}$), cleanliness must be stringently controlled, and processing times can be long at practical welding temperatures. One possibility is to employ an intermediate material that facilitates diffusion.

Another problem encountered in welding the refractory metals is related to their bcc structure. Body-centered cubic metals tend to form coarse-grained microstructures both during solidification and following recrystallization in the heat-affected zone, and they exhibit significant strain rate sensitivity. The strength, ductility, and toughness of bcc metals falls with increasing grain size, so any tensile stress in service or during post-weld cooling or processing concentrates strain in the heat-affected zone. Strain-rate sensitivity is thus increased, the tendency toward embrittlement is accentuated, and cracking may occur during cooling or in service upon repeated thermal cycling (i.e., due to thermal fatigue). The risk of cracking due to strain in these metals and alloys can be reduced by (1) using preheat (but not so much as to cause excessive grain growth in the heat-affected zone); (2) using post-weld heat treatment to reduce stresses; (3) selecting a filler that is softer than the base metals (to allow strain accommodation of building stresses in the fusion zone); and, above all else, (4) avoiding contamination.

When filler is required for fusion welding, it is generally selected to match the composition of the base material as closely as possible or be of a softer (i.e., lower-strength) composition. As an example, Mo–50Re or Mo–20Re filler is often used with pure Mo. Specific recommendations for specific refractory metals or alloys should be sought in appropriate references (such as the American Welding Society's *Welding Handbook*, 8$^{\text{th}}$ ed., Volume 3, "Materials & Applications," or ASM International's *Metals Handbook*, Volume 6, "Welding, Brazing, and Soldering"). While fillers are not normally used during resistance welding, brittleness may occur in spot-welded refractory metals like molybdenum. Brittleness can be minimized in Mo by inserting ductile foils (e.g, Zr, Ni, or Cu) or metal fiber between the faying surfaces of parts to be spot welded. Diffusion welding of refractory metals like Mo can also often be enhanced by using intermediate materials such as Ni.

11.2.4 Brazing the Refractory Metals and Alloys

The technology of brazing the refractory metals and their alloys is still in the development stage, with new techniques and brazing fillers being reported every day. Most refractory metals and alloys can be brazed to themselves and to other refractory metals and alloys. Care must be exercised in (1) selecting a compatible filler alloy, (2) relieving stresses before brazing, and (3) minimizing the time at brazing temperature to avoid embrittling reactions from absorption of gases or interdiffusion between filler and base material to produce intermetallics.

As general rules for tungsten and its alloys, (1) avoid brazing alloys with excessive Ni to prevent recrystallization in the base metal due to the high brazing temperatures required, and (2) avoid contact with graphite to prevent carbide formation.[5] For molybdenum and its alloys, (1) prevent oxidation by using protective coatings, (2) prevent contamination by interstitials, (3) prevent recrystallization by careful braze filler selection and braze cycle selection (limiting time over 1,090°C (2,000°F)), and (4) use barrier layers (e.g., Cr) to avoid diffusion-induced embrittlement by intermetallic compound formation with certain filler components (e.g., Ni). For tantalum and niobium and their alloys, (1) remove *all* reactive gases (e.g., O_2, CO, CO_2, N_2, H_2, NH_3) and (2) electroplate with Cu or Ni to prevent oxidation, and then use an appropriate filler that is compatible with the plating.

Table 11.3 lists some of the more common braze fillers used with various refractory metals and alloys.

11.3 JOINING REACTIVE METALS AND ALLOYS

11.3.1 Challenges Posed by Reactive Metals and Alloys

The reactive metals, which can include some of the refractory metals, present some difficult joining problems when welding or brazing is used, as well as when mechanical fastening is used. These metals (e.g., beryllium, titanium, and zirconium, as well as the refractory metals niobium, molybdenum, tantalum, and tungsten, and, to a lesser extent, aluminum and magnesium) have in common an extraordinarily high affinity for oxygen and other elements when they themselves are in their gaseous, liquid, and even solid forms. Some of the important properties of reactive metals are listed in Table 11.4.

In welding or brazing, which are often the preferred methods for joining metals, cleanliness of the workpieces is of special importance with the reactive metals and their alloys. Fluxes must be avoided or very carefully selected, and exposure to the atmosphere must be avoided when the base metal is hot or, especially, molten. The consequence of improper procedures is poor wetting and/or embrittlement of the resulting joint or, if the flux is too aggressive and not completely removed following use, severe corrosion.

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[5] This latter requirement may seem odd, but it is not. Graphite is itself highly refractory and thus is a likely candidate for use with tungsten and tungsten alloys.

Table 11.3 Common Braze Fillers for Use with Refractory Metals and Alloys

	Liquidus		*For use with*			
Filler	*°C*	*°F*	*W*	*Ta*	*Mo*	*Nb*
Ag	963	1765	✓		✓	
Au	1066	1950	✓		✓	
Cb or Nb	2468	4475	✓		✓	
Cu	1083	1981	✓		✓	
Ni	1453	2647	✓		✓	
Pd	1552	2826	✓		✓	
Pt	1769	3217	✓		✓	
BAg Series	618–971	1145–1780	✓		✓	
BAu Series	891–1166	1635–2130	✓		✓	
BNi Series	877–1135	1610–2075	✓		✓	
BCo–1	1149	2100	✓		✓	
Au–6 Cu	991	1815	✓		✓	
Au–50 Cu	971	1780	✓		✓	
Au–35 Ni	1077	1970	✓		✓	
Au–8 Pd	1241	2265	✓		✓	
Au–13 Pd	1304	2380	✓		✓	
Au–25 Pd	1410	2570	✓		✓	
Au–25 Pt	1410	2570	✓		✓	
Cr–25 V	1752	3185	✓		✓	
Pd–35 Co	1235	2255	✓		✓	
Pd–40 Ni	1235	2255	✓		✓	
Au–15.5 Cu–3 Ni	910	1670	✓		✓	
Au–20 Ag–20 Cu	835	1535	✓		✓	

	Liquidus		*Remelt*	*For use with*			
Filler	*°C*	*°F*	*°C (°F)*	*W*	*Ta*	*Mo*	*Nb*
10 Ta–40V–50 Ti	~1760	~3200	~2400 (4350)		✓		
20 Ta–50 V–30 Ti	~1760	~3200	~2400 (4350)		✓		
25 Ta–55 V–20 Ti	~1843	~3350	~2200 (4000)		✓		
30 Ta–65 V–5 Ti	~1843	~3350	~2400 (4350)		✓		
5 Ta–65 V–30 Nb	~1816	~3300	~2300 (4170)		✓		
25 Ta–50 V–25 Nb	~1871	~3400	~2500 (4530)		✓		
30 Ta–65 V–5 Nb	~1871	~3400	~2300 (4170)		✓		
30 Ta–40 V–30 Nb	~1927	~3500	~2000 (3630)		✓		
93 Hf–7 Mo	~2093	~3800	~2250 (4060)		✓		
60 Hf–40 Ta	~2193	~3980	~2150 (3880)		✓		
66 Ti–34 Cr	~1482	~2700	~2080 (3780)		✓		✓
66 Ti–30 V–4 Be	~1316	~2400	~2090 (3800)		✓		✓
48 Ti–48 Zr–4 Be	~1050	~1920	–				✓
75 Zr–19 Nb–6 Be	~1050	~1920	–				✓
91.5 Ti–8.5 Si	~1370	~2500	–				✓
73 Ti–13 V–11 Cr–3 Al	~1620	~2950	–				✓
90 Pt–10 Ir	~1815	~3300	–				✓

Table 11.3 (*Continued*)

Filler	Liquidus °C	Liquidus °F	Remelt °C (°F)	For use with W	Ta	Mo	Nb
90 Pt–10 Rh	~1900	~3450	–				✓
Nb	2416	4380	–	✓	✓	✓	
Ta	2996	5425	–	✓			
Ti	1816	3300	–	✓	✓	✓	✓

Filler	Liquidus °C	Liquidus °F	For use with W	Ta	Mo	Nb
Nb–2.2 B			✓			
Nb–20 Ti			✓			
Pt–3.6 B (+11 w/o W powder)			✓			
W–25 Os			✓			
W–50 Mo–3 Re			✓			
Mo–5 Os			✓			
V–35 Nb					✓	
Ti–30 V					✓	
Ti–8.5 Si (+ Mo powder)					✓	
Ti–25 Cr–13 Ni					✓	
Ti–65 V					✓	
V					✓	
V–50 Mo					✓	
Mo B–50 Mo C					✓	

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, pages 396, 397, Table 11.2, 1993, with permission of Elsevier Science, Burlington, MA.

Mechanical fastening and adhesive bonding can be used with these metals, but adhesive bonding is generally far less commonly used (an exception being Ti alloys in aerospace applications). When mechanical fastening is done, the fastener must be selected or specially fabricated from materials that will not galvanically corrode in the presence of these active materials. For example, Ti alloy fasteners work best with Ti alloys, Al alloy fasteners work best with Al alloys, etc. Coatings are often employed on mechanical fasteners used with reactive metals to provide an electrically insulating barrier as well as a general reaction barrier. But, not surprisingly, because coatings are thin they are prone to damage by scratching, and once the integrity of the coating is lost protection is lost. Adhesive bonding has been used most notably with titanium and its alloys, especially for joining lightweight structures such as honeycomb sandwich cores for use in aircraft and spacecraft. Adhesives are selected based on the adherends to be joined and the environment for service (see Chapter 5). Care must be taken to avoid unwanted reactions between the adhesive and the adherend(s), and during cleaning prior to bonding.

Table 11.4 Reactive Metals and Their Most Common Alloys

Metal or Alloy	*Melting Point °C (°F)*	*Density at 20°C g/cm³*	*Thermal Cond. W/m-°K (Btu/ft-h-°F)*	*Specific Heat J/kg-°K (10^{-2} Btu/lb_m-°F)*	*Elastic Modulus GPa(10^6 psi)*	*CTE at 20°C 10^{-6}°C^{-1}(°F^{-1})*
Niobium (Nb)	2,468 (4,474)	8.57	52.7 at 20°C (30.5 at 68°F)	-	105 (15)	7.3 (4.1)
Alloys			-	-		
1Zr–Nb (Nb–1Zr)						
5Mo–5V–1Zr–Nb (B–66)						
10Hf–1Ti–Nb (C–103)						
10W–1Hf–0.1Y–Nb (C–129Y)						
10W–2.5Zr–Nb (Nb–752)						
28Ta–11W–2.5Zr–Nb (PS–85)						
10Ta–10W–Nb (SN 6–29)						
Zirconium (Zr)	1,852 (3,350)	6.5	21 at 20°C (12.2 at 68°F)	290 at 20°C (6.9 at 68°F)	101 (14.4)	5.9 (3.3)
Alloys			-	285 (6.8)		
99.2(Zr+Hf), 4.5Hf max.						
97.5(Zr+Hf), 4.5Hf max.						
95.5(Zr+Hf), 4.5Hf max.						
Zr–1.5Sn, small Fe+Cr+Ni (Zircoloy-2)						
Zr–1.5Sn, small Fe+Cr (Zircoloy-4)						
Zr–2.5Nb						
Titanium (Ti)	1,668 (3,034)	4.5	17 at 20°C (9.8 at 68°F)	522 at 20°C (12.5 at 68°F)	117 (16.8)	8.4 (4.6)
Alloys			6–16 (3.5–9.3)	470–610 (11.2–14.6)		
Ti–5Al–2.5Sn						
Ti–6Al–4V						
Ti–6Al–2Sn–4Zr–2Mo						

Ti–6Al–2Sn–4Zr–6Mo						
Ti–13V–11Cr–3Al						
Ti–11.5Mo–6Zr–4.5Sn						
Beryllium (Be)	1,290 (2,355)	1.85	188 at 20°C (109 at 68°F)	188 at (20°C (45.2 at 68°F)	300 (44.5)	11.5 (6.4)
Be–38Al (Lockalloy)						
Aluminum (Al)	660.2 (1,220)	2.7	247 at 20°C (143 at 68°F)	900 at 20°C (21.5 at 68°F)	74 (10.5)	23.6 (13.1)
Alloys			88–243 (51–140)	856–963 (205–230)		
Al–Cu (2xxx)						
Al–Mn (3xxx)						
Al–Si (4xxx)						
Al–Mg (5xxx)						
Al–Mg-Si (6xxx)						
Al–Zn (7xxx)						
Al–Other (8xxx)						
Magnesium (Mg)	650 (1,202)	1.74	418 at 20°C (242 at 68°F)	1,025 at 20°C (24.5 at 68°F))	46 (6.5)	25.2 (14.0)
Alloys			51–138 (29.5–80.0)	960–1,050 (23.0–25.0)		
Mg–Al–Mn (AM alloys)						
Mg–Al–Zn (AZ alloys)						
Mg–RE–Zr (EK alloys)						
Mg–RE–Zn (EZ alloys)						
Mg–Th–Zr (HK alloys)						
Mg–Th–Mn (HM alloys)						
Mg–Zn–RE (ZE alloys)						
Mg–Zn–Th (ZH alloys)						
Mg–Zn–Zr (ZK alloys)						

11.3.2 Mechanically Joining the Reactive Metals and Alloys

Like all metal structures, mechanical joining of reactive metals and alloys using either mechanical fasteners or integral mechanical attachment features offers a technologically and economically viable approach. Without question, integral mechanical attachment features are the safer of the two broad alternatives (i.e., fastening and integral attachment). The reason is that integral features will obviously be compatible with the base component of which they are a part. If attachment is to be made to another material (regardless of its fundamental type or specific composition), no more, or less, attention is needed to ensure compatibility between the reactive metal or alloy and the other material than if integral attachments were not being used. When fasteners are used to accomplish mechanical joining, the material from which the fastener is made must be compatible with the reactive base metal or alloy. This can be done by using a fastener made of the same or very similar material, or by employing a coating that provides insulation and isolation of the fastener material from the material of the part. Inert coatings, often produced by physical vapor or chemical deposition, are commonly used on titanium or titanium-alloy fasteners used with materials other than titanium, especially graphite-fiber reinforced polymer-matrix composites. The purpose of such a coating is to provide electrical insulation to avoid galvanic interactions in which the non-reactive metal is usually the one to corrode sacrificially. Whenever such coatings are employed, care must be taken during installation and in service to prevent and preclude compromise of the integrity of the coating by scratching or rubbing, for example.

11.3.3 Welding the Reactive Metals and Alloys

The processes that have been employed with reactive metals and alloys include gas–tungsten arc welding (especially operating with DCSP or DCRP), gas-metal arc welding, plasma arc welding, electron beam welding, laser beam welding, resistance spot or seam welding, pressure and explosion welding, ultrasonic and various friction welding processes (including, quite recently, friction stir welding), and diffusion welding. The most common fusion processes, by far, have been GTAW, PAW, and EBW, without filler (i.e., autogenously). The most common non-fusion processes have been friction and diffusion welding, also without filler or intermediates. The principal problems encountered in welding reactive metals and their alloys are (1) embrittlement due to contamination, (2) embrittlement due to recrystallization, and (3) porosity due to contamination.

Beryllium,[6] titanium, zirconium, niobium, and tantalum all react rapidly at temperatures well below their melting points with all the common gases (e.g., O_2, N_2, H_2, CO_2, and H_2O vapor), but not with the inert gases (e.g., Ar and He).

[6] Besides being extremely reactive, beryllium is also extremely toxic in many forms, including as vapor, powder, dust, and chips. Consequently, extreme care should be exercised in welding, brazing, and soldering beryllium. The best advice is to leave it to experts!

To make matters worse, reactive metals, especially when they are hot or less molten, tend to dissociate water vapor (H_2O) and other gases (e.g., CO_2, NH_3, CH_4, and other hydrocarbon gases) into their component gases, and then react with those component gases. Contamination of the weld pool in these metals by oxygen and nitrogen absorbed from the air, for example, results in a dramatic increase in hardness (and strength) with a dramatic loss of ductility and toughness, even under fairly effective shielding. Trace amounts of air or water vapor in inert atmospheres or vacuums lead to severe contamination of Ti and Zr, for example. Besides reacting with gases, many of the reactive metals (most notably Ti) react with virtually every other element, both non-metallic and metallic, in ionic, liquid, and even solid forms.

For the most effective shielding with GTAW or PAW, the following methods should be used: (1) both the torch side and the underside of the joint should be blanketed with inert gas that itself has been dried with desiccating filters; (2) a trailing shield on the torch should be considered to allow the weld to solidify and cool under the protection of the inert shielding gas; and (3) a dry box,[7] glove box, or tent containment should be employed whenever possible. For the most stringent applications, where prevention of contamination is critical, a vacuum atmosphere of better than 10^{-4} torr should be used with an EBW source. Resistance welding (and even flash welding) has been performed successfully in air because the time cycle (i.e., time at temperature) is too short for any substantial degree of gas pickup. Figure 11.3 schematically illustrates some special techniques for shielding reactive metals and alloys during welding.

Porosity can be a serious problem in welding reactive metals and their alloys. Porosity can arise from the release of dissolved gases in the metal (e.g., introduced during metal production, post-processing, or subsequent fabrication processing such as acid pickling), from gases entrapped in tooling (i.e., incipient leaks), from entrapped gases in the metal (e.g., from powder processing by compacting), or from other sources (e.g., poor cleaning). Hydrogenation of Ti and Zr is a particular problem resulting in severe and persistent porosity in the weld fusion zone and/or embrittling hydrides in the fusion zone and/or heat-affected zone. Effective precleaning is critical to the successful welding of reactive metals and is accomplished by machining, scraping, grit blasting, or grinding followed by degreasing or careful pickling.

Cracking of reactive metals and their alloys can be a problem during welding. The unalloyed reactive metals are not especially prone to hot cracking, nor are their alloys, which are typically welded. The brittle metals beryllium, molybdenum, and tungsten, however, may crack at low temperatures due to strain sensitivity if welded under restraint. Post-weld stress relieving and proper joint design help prevent such cracking.

The reactive metals and their alloys are fusion-welded either autogenously or using fillers that closely match the base metal or alloy in composition and properties. Specific filler recommendations are available in the AWS and ASM handbooks referenced at the end of this chapter.

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[7] A "dry box" is a chamber for allowing welding (or other processing) under inert shielding. Rubber gloves attached to the box (giving rise to the name "glove box"), along with sealed viewing ports, allow an operator to gain access to a welding torch inside the shielding environment to perform manual welding.

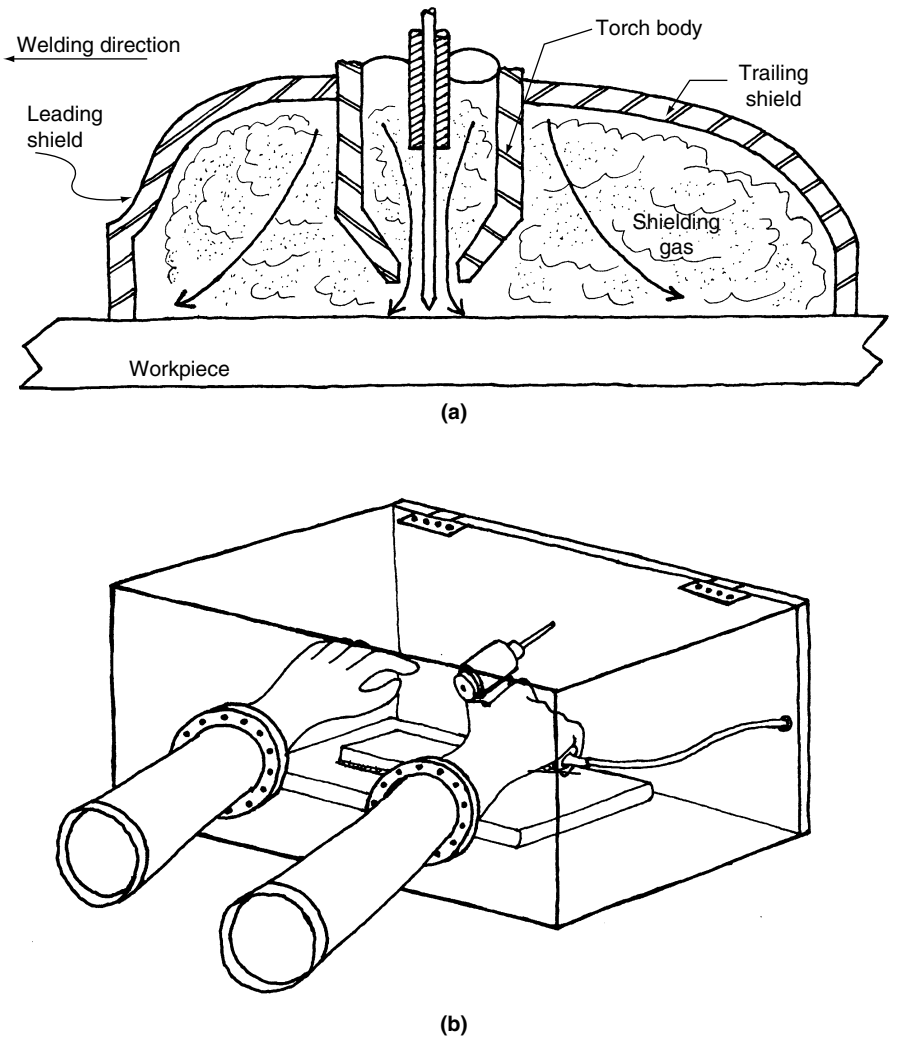

Figure 11.3 Schematic illustration of special techniques for shielding reactive metals and alloys during fusion welding, including a torch nozzle leading and/or trailing shroud or shield (a) and glove box or dry box (b).

11.3.4 Brazing the Reactive Metals and Alloys

Brazing is an attractive alternative for joining most reactive metals and alloys and is the preferred method for metallurgically joining beryllium, since dangerous Be vapor is not generated. Because of the chemical and metallurgical reactivity of most reactive metals and their alloys, brazing techniques must be highly specialized. Filler alloys must be chosen carefully to avoid undesirable reactions.

For beryllium, the preferred brazing alloys are zinc (with a melting range of 427–454°C (800–850°F)), aluminum–silicon (566–677°C (1,050–1,250°F)), silver–copper (649–904°C (1,200–1,660°F)), and silver (882–954°C (1,620–1,750°F)). For titanium and zirconium, embrittlement by surface contaminants, the atmosphere, insufficiently protective shielding gases, and even certain components of fluxes (e.g., chlorine for Ti) must be avoided by very careful cleaning, immediate brazing, and careful flux selection and use. Acceptable fillers for Ti are (1) 3003 Al foil for thin, lightweight structures (e.g., honeycomb core); (2) electroplated metals such as Cu, Fe, or Ni on the Ti to react *in situ* during brazing to form a eutectic with the titanium; (3) silver-based alloys with Li, Cu, Al, or Sn, including an especially good Ag–9Pd–9Ga alloy for filling large gaps; (4) 48Ti–48Zr–2Be; (5) 43Ti–43Zr–12Ni–2Be; and (6) various Ti–Ni–Cu alloys. A big problem in selecting appropriate filler for Ti and its alloys is achieving reasonable corrosion resistance in the brazed joint, since Ti is often chosen for its excellent corrosion resistance. The Ti–Zr–Be and Ti–Zr–Ni–Be fillers just given offer excellent corrosion resistance. For zirconium and its alloys, good braze fillers have long been sought. Some successes are 95Zr–5Be (1,004°C (1,840°F)), 50Zr–50Ag (1,521°C (2,770°F)), 71Zr–29Mn (1,371°C (2,500°F)), and 76Zr–24Sn (1,732°C (3,150°F)), as well as Zr–4-5%Be, Ni–7%P, or Ni–20%Pd–3%In.

Table 11.5 lists some important braze fillers for use with reactive metals and alloys.

11.3.5 Adhesive Bonding the Reactive Metals and Alloys

Adhesive bonding can be an acceptable method for joining reactive metals, provided the service environments are not degrading to the adhesive. However, this caveat really restricts the use of adhesive bonding with reactive metals. Ti and Zr both offer exceptional resistance to corrosion and modest resistance to elevated temperatures. Clearly, the use of polymeric adhesives for such applications is not viable. On the other hand, adhesives might be an excellent choice for joining reactive metals to other metals, as the adhesive, if polymeric, would electrically insulate the one metal from the other and prevent unwanted galvanic interaction and corrosion. Zr is widely used in nuclear applications, but the use of polymeric adhesives, while possible, must be undertaken very carefully as polymers can be quite prone to degradation by many types of radiation. Because Be, Al, Mg, and Ti all have low densities (i.e., 1.85 and 4.51 g/cm^3, respectively), and, except for Ti, are all low melting, these metals or their alloys are often selected for uses where weight is critical, as in aircraft and spacecraft. For such applications, polymeric adhesives can be a good choice for joining provided they can tolerate the service environment. Adhesives do not require these adherends to be heated. They provide strong joints without adding much weight, and are ideal for use with thin members, which are likely choices for weight-critical applications.

Table 11.6 lists various types of polymeric adhesives suitable for use with reactive metals and alloys.

Table 11.5 Special Braze Fillers for Reactive Metals and Alloys

Filler Alloy	Brazing Range (°C/°F)
For Be and Be alloys	
Zn	425–455/800–850
Al–Si (7–12% Si)	565–605/1,050–1,120
Al	645–655/1,190–1,215
Ag–Cu (e.g., 7Cu–0.2Li)	650–905/1,200–1,660
Ag	880–955/1,620–1,750
For Nb and Nb alloys	
Pd	1,550–1,600/2,825–2,915
Pd–Cu	-
Ti	1,816/3,300
Ti–11Cr–13V–3Al	1,650/3,000
Ti–30V–4Be	1,290–1,315/2,350–2,400
Ti–33Cr	1,455–1,480/2,650–2,700
Ti–8.5Si	1,455/2,650
For Ti and Ti alloys	
48Ti–48Zr–4Be	870–955/1,600–1,700
43Ti–43Zr–12Ni–2Be	870–955/1,600–1,700
Ag–9Pb–9Ga	900–915/1,650–1,675
95Ag–5Al	870–915/1,600–1,650
92.5Ag–7.5Cu	-
AA3003 (for Ti honeycomb)	645–655/1,190–1,210
AA4043 (for Ti honeycomb)	595–615/1,100–1,135
For Zr and Zr alloys	
Zr–50Ag	1,520/2,770
Zr–29Mn	1,780/3,235
Zr–25Sn	1,730/3,145
Zr–5Be	970–990/1,780–1,815
For Al and Al alloys	See Table 11.8
For Mg and Mg alloys	See Table 11.8

11.4 JOINING HEAT-SENSITIVE METALS AND ALLOYS

11.4.1 Challenges Posed by Heat-Sensitive Metals and Alloys

Some metals and alloys are quite sensitive to heat, so joining them must be done either without using heat (e.g., using adhesive bonding, mechanical fastening, or integral attachment), or using processes that require heat (e.g., welding, brazing, or soldering), but controlling the heat input to the joint elements very carefully or localizing the heat as much as possible. Sensitivity to heat in metals and alloys can be manifested in any one of several ways. First, localized melting or burn-through can occur in low-

Table 11.6 Recommended Adhesives for Use With Reactive Metals and Alloys

For Nb and Nb alloys	See Ti and Ti alloys below
For Zr and Zr alloys	See Ti and Ti alloys below
For Ti and Ti alloys	
Epoxies	Epoxy–phenolics
Nitrile–epoxies	Nitrile–phenolics
Polyimides	
For Be and Be alloys:	
Epoxies	Epoxy–nitrile
Epoxy–nylon	Epoxy–phenolics
Nitrile–phenolics	Polyimides
Polybenzimidazoles	Polyurethanes

melting and/or high thermal conductivity metals of alloys such as Al, Mg, Zn, Sn, Pb, and their alloys, Cu-based brasses and bronzes, and even precious metals Ag, Au, Pt, and Pd and their alloys. Second, softening and/or loss of strength can occur in quenched and tempered (i.e., transformation-hardened) steels with medium to high C contents and/or low to high alloy contents, in age-hardened alloys (e.g., Al- and Ni-based alloys and PH stainless steels), or in cold-worked or strain-hardened metals or alloys (e.g., spring-tempers in brasses or certain austenitic stainless steels). Third, loss of ductility, embrittlement, and/or cracking can occur in alloys that undergo certain cooling rate-related phase transformations (e.g., hardenable steels) or that cannot tolerate thermal shock because of their inherent brittle nature (e.g., cast irons).

Another possible manifestation of heat sensitivity is adverse reactions with the surrounding atmosphere (e.g., embrittlement by adsorption of gases, such as oxygen, nitrogen, or hydrogen interstitially) or with adjoining materials (e.g., Fe near Ti, or Cu near austenitic stainless steels). Since this occurs most commonly with the refractory and reactive metals and alloys described in Sections 11.2 and 11.3, it will not be discussed again here.

If welding or brazing, or, to a far lesser extent, soldering are chosen for joining heat-sensitive metals and alloys, care must be exercised to minimize the amount, the concentration, and the duration of heating. Obviously, mechanical joining and adhesive bonding using adhesives that do not require significant heat to cure or generate significant heat upon curing may be the preferred joining options for these materials.

11.4.2 Welding the Heat-Sensitive Metals and Alloys

The welding of heat-sensitive cold-worked, age-hardened, or transformation-hardened alloys was discussed in Chapter 9, Section 9.5, so it will not be repeated here. Suffice it

Table 11.7 Heat-Sensitive (Low-Melting or High-Conductivity) Metals and Alloys

Metal or Alloy	*Melting Temp. °C(°F)*	*Boiling Temp. °C(°F)*	*Density at 20°C g/cm³*	*CTE* 10^{-6} °C^{-1}(°F^{-1})	*Thermal Cond. W/m-°K (Btu/ft-h-°F)*	*Specific Heat J/kg-°K* (10^{-2} *Btu/lb$_m$-°F)*
Aluminum	660.2 (1,220)	~2,500 (~4,530)	2.7	23.6 at 20°C (13.1 at 68°F)	247 at 20°C (143 at 68°F)	900 at 20°C (21.5 at 68°F)
Al alloys			2.6–2.9	18.0–24.5 (10.0–13.6)	88–243 (51–140)	856–963 (205–230)
Copper	1,084 (1,983)	~2,500 (~4,530)	8.92	17.0 at 20°C (9.4 at 68°F)	398 at 20°C (230 at 68°F)	386 at 20°C (9.2 at 68°F)
Cu alloys			7.45–9.40	15.8–22.0 8.8–12.2	12–391 7–226	373–440 8.9–10.5
Gold	1,063 (1,945)	~2,850 (~5,165)	19.3	14.2 at 20°C (7.9 at 68°F)	80 at 20°C (46 at 68°F)	128 at 20°C (3.1 at 68°F)
Lead	327.4 (621)	1,750 (3,185)	11.34	29.3 at 20°C (16.3 at 68°F)	34 at 20°C (19.7 at 68°F)	129 at 20°C (3.1 at 68°F)
Magnesium	650 (1,202)	1,103 (2,067)	1.74	25.0 at 20°C (13.9 at 68°F)	418 at 20°C (242 at 68°F)	1,025 at 20°C 24.5(at 68°F)
Mg alloys				25.0–27.0 (13.9–15.0)	51–138 (29.5–80.0)	960–1,050 (23–25)
Palladium	1,552 (2,826)	-	12.0	11.1 at 20°C (6.2 at 68°F)	-	-
Platinum	1,769	-	21.5	9.5 at 20°C (5.3 at 68°F)	71.1 at 20°C (41.1 at 68°F)	132 at 20°C (3.2 at 68°F)
Silver	960.5 (1,761)	2160 (3,920)	10.5	19.7 at 20°C (10.9 at 68°F)	428 at 20°C (247 at 68°F)	235 at 20°C (5.6 at 68°F)
Tin (β)	231.9 (449)	~2,400 (~4,350)	7.30	23.8 at 20°C (13.2 at 68°F)	17 at 20°C (9.8 at 68°F)	222 at 20°C (5.3 at 68°F)
Zinc	419.5 (787)	907 (1,665)	7.14	39.7 at 20°C (22.0 at 68°F)	113 at 20°C (65 at 68°F)	382 at 20°C (9.1 at 68°F)
Cast Fe (gray)	1180–1150	-	7.3	11.1–12.6 at 20°C	46.0–57.3 at 20°C	540 at 20°C
Steel, plain C	1350–1540	-	7.85	11.0–12.0 at 20°C	50–65.3 at 20°C	480–500 at 20°C
Steel, HSLA	1350–1540	-	7.85	11.1–12.8 at 20°C	37.5–48.9 at 20°C	450–480 at 20°C
Austenitic stainless	1505–1550	-	8.0	15.0–17.5 at 20°C	14.4–17.2 at 20°C	500 at 20°C

to say that some heat-sensitive alloys of these types include but are not limited to (1) cold-worked brasses, bronzes, beryllium–copper alloys, and stainless steels; (2) age-hardenable aluminum alloys, including Al–Cu, Al–Cu–Mg, Al–Mg–Si (2xxx and 6xxx) types, Al–Mg–Zn (7xxx) types, and new Al–Li types; (3) age-hardenable magnesium alloys, including Mg–Al–Mn types like A8, A10, and A12, and Mg–Al–Zn–Mn types like AZ63, AZ92, and AZ101; (4) age-hardenable nickel-base alloys, including those with controlled additions of Mg, Be, Al, Si, Ti, and Mo such as the "K," "KR," and "S" Monels and the Hastelloy A, B, and C types, as well as superalloys such as the Inconels, Udimets, Nimonics, Rene's, and Waspaloys; (5) age-hardenable Co-based alloys, including those strengthened by complex carbides such as Co–Cr–C and Co–Cr–Mo–C types, and those hardened by intermetallics, such as the Co–Cr–Mo with Co_3Mo, Co–Cr–Ta, W, or Nb and Co–Ti or Co–Cr–Ni with Ni_3Ti as in the Haynes and Haynes Stellite alloys; (6) age-hardenable steels, including maraging steels and precipitation-hardening (PH) stainless steels such as 17-4PH and 15-5PH; (7) hardenable carbon and alloy steels, including heat-resistant, corrosion-resistant, and tool steels; and (8) cast irons.

Some general guidelines for welding heat-sensitive metals and alloys follow. First, use a process that minimizes heating and melting, such as non-fusion friction or pressure welding or resistance welding, the latter of which has an extremely rapid heating rate and an extremely short time at elevated temperature. Second, use fusion welding processes that minimize net linear heat input (i.e., joules per millimeter or kilojoules per inch) by employing high welding speeds with GTAW, GMAW. Other especially good options are high-energy density (inherently high-speed) processes like EBW or LBW. Third, use pulsed-current modes with GTAW, GMAW, or PAW to lower the average current and power. Fourth, use electrode-positive DC or AC operating modes to shift the bulk of the heat of the arc from the workpiece to the electrode. Fifth, use preheating with transformation hardenable alloys to reduce the cooling rate after welding. Sixth, minimize joint thickness and the number of passes. Seventh, maintain low interpass temperatures by waiting between passes or by moving to different locations to allow cooling in previous weld areas. Finally, use intermittent ("stitch" or "skip") welding techniques to reduce the total heat input to the joint.

The welding and brazing of low-melting as well as high thermal conductivity metals and alloys present special problems. Tin (232°C (450°F)), lead (327°C (620°F)), zinc (420°C (788°F)), magnesium (650°C (1,202°F)), aluminum (660°C (1,220°F)), and their alloys have low melting temperatures, as do certain copper-based alloys such as the brasses (i.e., Cu–Zn alloys) and bronzes (i.e., Cu–Sn alloys). These are shown in Table 11.7 along with some useful properties. In addition, Al, Mg, Cu, and the precious metals Ag, Au, Pt, Pd, and others, have very high thermal conductivities compared to most other structural metals and alloys (e.g., steels, Ni-based, and Ti-based alloys).

A low-melting metal or alloy can cause problems because many such metals and alloys do not give any visual indication of how hot they are (i.e., they do not emit visible radiation or color change in the form of light as steels do, for example). This presents problems to a human operator who is relying on biofeedback as a means of controlling

heat input. Also, such metals can tolerate only so much heat input before melting occurs. With many of the higher intensity welding heat sources (e.g., arcs, plasmas, and beams), excessive heating and melting can easily occur or vaporization can quickly follow melting, which can lead to burn-through by either "molten metal drop-out" or vaporization. To add to this problem, many of these metals and alloys oxidize easily and form a refractory oxide layer (e.g., Al and Mg form Al_2O_3 and MgO). Consequently, enough heat must be applied to disrupt the oxide but not so much that it burns through the weldment. There is a tendency to apply too much heat.

The property of high thermal conductivity (e.g., in Al, Cu, and the precious metals) means that heat from the welding source disperses quickly from the point of energy deposition into the surrounding material. Thus, there is a tendency (especially with manual processes) to dwell too long to compensate for this high conduction. This often results in localized overheating and burn-through. If one thinks about welding aluminum alloys versus steels, for example, aluminum has a thermal conductivity that is three to five times greater than steel's but has half of steel's absolute melting temperature. Thus, heat input must be kept very low when welding aluminum and its alloys.

Aluminum, magnesium, and their alloys are typically welded at high speeds with GTAW for thinner sections, with GMAW for thicker sections, or with EBW for very thick sections or for special, precision applications. Zinc, lead, and their alloys are usually welded with either GTAW or oxy-fuel gas processes (such as oxy-acetylene). The precious metals and their alloys are usually welded with oxy-fuel gas processes (manually) but can be welded with GTAW using DCSP. To help keep the heat input low, smaller diameter tungsten electrodes tend to be used with GTA when welding these metals and alloys. Resistance welding also works well with this entire group of materials, except zinc and lead and their alloys, where ever-present oxides cause severe sticking to Cu electrodes.

Resistance and various non-fusion processes are often good choices for welding heat-sensitive metals and alloys, in general. Resistance welding of Al and Mg was mentioned previously. Friction and pressure welding, as well as diffusion welding, have been successfully used with at least some of the heat-sensitive materials. A requirement is that the material has enough ductility to permit some essential upset during non-fusion welding. Consequently, cast iron is not a viable candidate for these processes. Ni- and Co-based superalloys, however, as well as Al, Mg, and some Cu alloys, are joined by these processes, including DFW.

11.4.3 Brazing and Soldering Heat-Sensitive Metals and Alloys

Brazing and soldering are good choices for joining heat-sensitive metals and alloys. Strong adhesion can be obtained with brazing at moderate temperatures and heat input, while sound joints can be obtained with soldering at low temperatures and heat inputs. Age-hardenable alloys, such as those of Al, Mg, Ni, and Co, can all be

brazed with minimal effects on aged properties if heating is properly localized through proper process selection. Aluminum and magnesium and their alloys present a problem in wetting because of their inherent and tenacious refractory oxides. Torch, furnace, and dip processes are commonly used, with induction, infrared, and resistance processes being used for special situations. Aggressive (usually inorganic acid or salt-based) fluxes are often required for achieving good wetting. Brazing cycles (i.e., time at the brazing temperature) should be kept short to minimize penetration of the filler components by diffusion, which could lead to adverse brittle compound or low-melting eutectic formation.

For Al and its brazeable alloys, BAlSi fillers are used. This poses an unusual complication in the brazing of Al alloys not normally encountered in brazing. The Al–Si fillers have liquidus temperatures that are extremely close (often within 30°C (50°F) with needed superheating) to the solidus of the Al alloys of the brazement components. Controlling temperatures in the brazing of Al alloys is thus absolutely critical and is especially difficult. For this reason, the high-strength wrought alloys and certain cast alloys, with their high alloy contents and low melting temperatures (i.e., solidus temperatures), are not generally brazed. The 2xxx and 7xxx alloys commonly used in aerospace applications fall into this category. For magnesium and its alloys, BMg fillers are used, including BMg1 (9Al–2Zn–0.1Mn–0.00005Be) and BMg2 (12Al–0.5Zn–0.00005Be). Problems similar to those encountered trying to braze Al alloys occur for Mg alloys because of the closeness of the braze filler's liquidus and the base alloy's solidus temperatures. Two solders are used for filling in defects in magnesium castings are 60Cd–30Zn–10Sn (with a 150°C (300°F) melting temperature) and 90Cd–10Zn (with a 300°C (575°F) melting temperature. Surprisingly, given the reactivity of Mg, no fluxes are usually required or used with Mg or its alloys.

The age-hardenable, heat-sensitive Ni- and Co-based alloys, including most of the so-called "superalloys" used in high-temperature applications (e.g., aircraft gas turbines) can be successfully brazed. BNi or BAu fillers are used with the Ni alloys and BCo fillers are used with the Co alloys.

For applications where mechanical strength is not critical, or where the melting temperature of the metal or alloy to be joined is especially low (e.g., Sn, Pb, Sn–Pb alloys, Zn, and Zn alloys), soldering can be an excellent choice. Aluminum, brasses, bronzes, zinc die-casting alloys (known as "white metal"), and tin- and lead-based Babbitt alloys are frequently soldered very successfully. Magnesium is essentially impossible to solder because of the difficulties in achieving wetting. For aluminum and its alloys, aggressive inorganic acid or salt fluxes are required, and solder fillers include Sn–Pb, Sn–Zn, Pb–Bi, Zn–Cd, and Pb–Cd–Sb–Ag types. Silver is added to many solders to improve the generally poor corrosion resistance of solder joints in aluminum. One example is 80.1Pb–18Sn–1.9Ag. The precious metals and their alloys can also be successfully soldered.

Table 11.8 lists braze fillers and solders most commonly used with heat-sensitive metals and alloys of various types.

Table 11.8 Braze Fillers and Solders for Heat-Sensitive Metals and Alloys

Metal or Alloy		*Braze Filler or Solder*	*Brazing or Soldering Temperature* (°C/°F))
For Al or Al alloys		BAlSi (see Table 7.3)	
		Zn–0.5Al	375–419/710–787
		Zn–10Cd	265–405/509–700
		Zn–20Cd	265–335/509–635
		Sn–Zn (15–70Zn) solders	110–335/230–500
		50Sn–50Cd solder	180–215/310–420
For Cu or Cu alloys		BAg (see Table 7.3)	
		BAu (see Table 7.3)	
		BCuP (see Table 7.3)	
		RBCuZn (see Table 7.3)	
		Sn–Pb solders (see Table 8.3)	
		Sn–Sb solders (see Table 8.3)	
		Sn–Ag solders (see Table 8.3)	
For precious metals or alloys			
Ag		BAg–9 (64–66Ag/19–21Cu/13–17Zn)	671–713/1,240–1,325
		BAg–10 (69–71Ag/19–21Cu/8–12Zn)	690–738/1,275–1,360
Au	Yellow	42Au–24Ag–16Cu–9Zn–9Cd	630–700/1,170–1,295
		42Au–35Ag–22Cu–1Zn	730–745/1,340–1,375
		58Au–18Ag–12Cu–12Zn	720–755/1,330–1,390
		58Au–21Ag–15Cu–6Zn	775–800/1,425–1,470
	White	42Au–30Ag–8Cu–15Zn–5Ni	700–730/1295–1,350
	Dental	47Au–15Ag–35Cu–3Sn	657–775/1,215–1,425
		62Au–16Ag–13Cu–4Zn–2Sn	770–810/1,420–1,490
		65Au–16Ag–13Cu–4Zn–2Sn	740–800/1,365–1,470
		82Au–8Ag–8Pd–2Sn	1,090–1,105/1,995–2,020
Pd		Au/8–35Pd	1,240–1,440/2,260–2,625
Pt		Au	1,065–1,125/1,945–2,045
		Au/20–30Pd (to match color)	–
For Pb or Pb alloys		Pb/30–40Sn/0–2Sb solders	183–249/360–480
		50Pb–50Sn solder	183–216/360–420
For Sn or Sn alloys		Sn solder for Sn or Sn alloys (see Table 7.3)	
		Sn–Ag solders for Sn–Pb alloys (see Table 7.3)	
		Sn–Pb solders for Sn–Pb alloys (see Table 7.3)	
		Sn–Zn solders for Sn–Zn alloys (see Table 7.3)	
For Zn or Zn alloys		Sn–Zn solders (see Table 7.3)	
		Cd–Zn solders (see Table 7.3)	
		In solders (see Table 7.3)	
For cast irons		BAg–1, 1a, or 2 (see Table 8.3)	1,090–1,150/2,000–2,
		RBCuZn (see Table 8.3)	

11.4.4 Adhesive-Bonding Heat-Sensitive Metals and Alloys

Adhesive bonding can be very successfully applied to heat-sensitive metals and alloys, but it is usually restricted to use with the lower-melting metals and alloys that tend to be employed to fulfill applications at lower service temperatures. Adhesive bonding is extremely useful for joining thin section and/or lightweight structures. The best examples are probably the bonding of aluminum and magnesium alloys, including extra low density aluminum–lithium and magnesium–lithium alloys. It is also not uncommon to find weld-bonding being used with these lightweight materials, especially when out-of-plane loading is possible or required. Adhesive bonding is usually not used with the heat-sensitive alloys intended for elevated temperature service, such as Ni- and Co-base superalloys, for reasons of environmental degradation.

Table 11.9 lists adhesives that are recommended for use with various lightweight or low-melting metals and alloys.

11.4.5 Mechanically Joining Heat-Sensitive Metals and Alloys

Obviously, mechanical fastening and integral mechanical attachment methods are excellent options for joining heat-sensitive metals and alloys, as no heat is needed to accomplish joining. For mechanical fastening and integral attachment, the same general principles apply to avoid overloading the fasteners and joint elements (see Chapter 2, Subsection 2.4.4). For low-melting metals and alloys (e.g., Sn, Pb, and Zn)[8] as well as the precious metals (e.g., Ag, Au, Pt, and Pd) that also tend to be soft, deformation of the fastener hole or a design feature by bearing and/or fastener tear-out or feature pull-out must be carefully considered and avoided. Techniques include the use of harder metal/alloy sleeves in holes, more generous radii on features, use of reinforcements (e.g., doublers) around holes, and other techniques that lessen point loading and stress concentration. For the inherently brittle, thermal shock–sensitive alloys such as zinc die-cast alloys or cast irons, care must also be exercised in hole preparation and loading. In addition, care should be exercised to avoid problems with thermal mismatch due to the development of intolerable stresses from differential thermal expansion/contraction. This is especially true with high thermal conductivity metals like copper, aluminum, magnesium, and the precious metals, or with metals and alloys (or other materials) that are expected to function over wide temperature ranges, such as Ni- and Co-base superalloys. Finally, normal precautions should be taken regarding potential galvanic corrosion couples, especially with the precious or "noble" metals.

[8] There is an expected relationship between strength or hardness and melting point, as both arise from the bond strength in the material. Lower melting point materials tend to be softer and less strong than higher melting point materials.

Table 11.9 Recommended Adhesives for Use With Heat-Sensitive Metals and Alloys

Metal or Alloy	*Adhesives*		
For Al or Al alloys			
	Modified epoxies	Nitrile-epoxies	Silicones
	Modified acrylics	2nd-generation acrylics	Cyanoacrylates
	Epoxy–phenolics	Neoprene–phenolics	Vinyl plasticols
For Cu and Cu alloys			
	Acrylics	Cyanoacrylates	Anaerobics
	Epoxies	Nylon–epoxy	Nitrile–epoxy
	Neoprene–epoxy	Polyurethanes	Silicones
For precious metals and alloys			
Ag	Epoxies	Polyvinyl alkylether	
Au	Anaerobics	Epoxies	Epoxy–phenolics
	Polyvinyl alkylether		
Pd	See Au		
Pt	See Au		
For Pb or Pb alloys			
	Cyanoacrylates	Polyacrylates	Polyvinyl alkylether
	Epoxies	Epoxy–phenolics	Polyurethanes
	Silicones		
For Sn or Sn alloys			
	Epoxies	Polyacrylates	Polyvinyl alkylether
	Styrene–butadiene		
For Zn or Zn alloys			
	Epoxies	Nitrile–epoxy	Cyanoacrylates
	Silicones	Rubber-based adhesives	
For cast irons			
	Acrylics	Epoxies	Polyimides
	Nitrile–phenolics	Epoxy–phenolics	Rubber-based adhesives

11.4.6 Welding, Braze Welding, and Brazing Cast Irons

Cast irons are very high carbon iron–carbon alloys, typically containing 2–5 wt.% C along with between 1.0 wt.% and over 3.5 wt.% Si, and other minor additions. As a group, cast ions are hard and brittle and highly susceptible to thermal shock.[9] Their value is for their ease of casting of large and complex shapes possessing high to very high strength, good to excellent wear resistance, excellent damping characteristics for

[9] Some materials science textbooks give a parametric relationship for the thermal shock resistance (TSR) of a material as TSR $\sim [(\sigma_f)(k)]/[(E)(\alpha)]$, where σ_f = fracture strength, k = thermal conductivity, E = modulus of elasticity, and α = coefficient of thermal expansion. A high value of TSR indicates better resistance to thermal shock.

vibrations (for those types containing graphite flakes or nodules), and good to poor machineability (depending on microstructure, with those with a steel matrix surrounding graphite flakes or nodules having better machineability). For these reasons, cast irons are widely used for producing heavy support frames for machine tools, manhole covers and sewer gratings, decorative façades, and many other objects. Cast irons are an extremely important group of alloys both technologically and economically.

Cast irons come in several different types, based on method of production and generation of a particular microstructure (most notably characterized by the size and shape or morphology of the carbon and/or cementite phases). They also come in many different grades, based on strength level within each type. But all cast irons have the common characteristics and attributes of especially low melting temperature (among iron–carbon alloys) and high fluidity, leading to good castability. Major types include (1) white cast irons (where C exceeds 1.7 wt.% and is all combined in the form of iron carbide or cementite); (2) gray cast irons (where C ranges from 2 wt.% to almost 5 wt.% and is in the form of flakes of graphite embedded in a steel matrix); (3) mottled cast irons (which are a cross between white and gray cast irons obtained by composition and cooling rate control from the melt); (4) malleable or ductile cast irons (where the cementite has dissociated in the solid state by heat treatment into small particles or nodules of graphite); and (5) nodular or spheroidal graphite (SG) cast irons (where graphite nodules are formed directly from the melt through the use of inoculants and are embedded in a matrix of steel). White cast irons, for all intents and purposes, are not weldable (due to their very poor thermal shock resistance) but can be brazed, if done properly. The other types are weldable if proper procedures are employed, and all can be brazed as well. The detailed metallurgy of the various types of cast iron is left to other sources (e.g., the *AWS Welding Handbook*, 8th ed., Volume 3). Only the welding, braze welding, and brazing of these technologically and economically important alloys will be discussed here.

Gray cast iron is the most common and least costly of all the cast materials, so it is very widely used. It is composed of 2.5–3.5 wt.% C in iron, in which most of the carbon is present as free graphite flakes. These flakes promote brittleness and sensitivity to thermal shock since they look and act like cracks but provide excellent damping characteristics due to their creating high internal friction to propagating elastic waves. Additions of phosphorus to enhance fluidity for casting and impurities of sulfur promote hot shortness in the form of hot cracking. The spheroidal graphite (nodular) and ductile (malleable) types are rendered much more ductile by causing the carbon to come out as graphite in the form of spheres or nodules by either special heat treatment of white cast irons or the addition of graphitizing agents or inoculants such as Mg, Ni, or rare earth elements (e.g., Ce) to the melt.

The metallurgical changes that take place in the heat-affected zone of fusion welds in gray and spheroidal (nodular) cast irons are basically the same. In the region heated above the eutectoid temperature, the ferrite is transformed to austenite. Above 800°C (1,370°F), graphite starts to go into solution and, simultaneously, cementite is precipitated, first at grain boundaries and, at higher temperatures when more graphite is dissolved, within the austenite grains. At still higher temperatures, some melting occurs by constitutional liquation (which is melting due to diffusion-induced

composition gradients during non-equilibrium heating). On cooling, the cementite network remains but austenite transforms high carbon regions to martensite and low carbon regions to pearlite. Thus, the heat-affected zone of fusion welds in cast irons has a complex structure composed of melted and remelted regions, undissolved graphite, martensite, fine pearlite, coarse pearlite, and some ferrite. This structure is often very hard and very brittle, and, when tested in tension or bending, usually fails through or along the FZ–HAZ boundary.

Welding

During fusion welding, the effects described previously can be mitigated in several ways. First, by preheating to about 300°C (570°F) and using low-hydrogen electrodes, hard zone (martensite) formation and cracking will be minimized and hydrogen cracking will be avoided. Second, post-weld heat treatment at 650°C (1,200°F) or full annealing will reduce HAZ hardness even more. Third, when preheating is not possible or practical (e.g., due to size and/or the site at which welding will be done), heat input should be reduced to the lowest possible level by operating in DCRP, by making short runs (i.e., skip or stitch welding), or by allowing cooling between each run to minimize the interpass temperature. This technique reduces graphite dissolution and, hence, hardenability. Fourth, after welding, the cast iron weldment should be cooled slowly to avoid thermal shock. Insulating blankets or even resistance-heated blankets can be used.

Cast iron can be welded with various fillers, using the oxy-fuel gas (OFW), SMAW, FCAW, GTAW, GMAW, PAW, or SAW processes. In gas welding, a cast-iron filler rod is often used. The two most common fillers for arc welding are pure Ni and 55Ni–45Fe. These are available in both electrode and wire forms. The relatively low strength and high ductility of these fillers allows stresses generated from the heat (especially nonuniform heat) of welding to concentrate in the weld proper. The low melting point of these fillers minimizes hardening effects.

A common procedure for welding cast irons is known as ''buttering.'' Here, a soft Ni or Ni–Fe (or even an austenitic stainless steel) is applied in thin, narrow short passes on each faying surface, to coat or ''butter'' the base metals. Then the joint is filled to complete the weld, usually using 55Ni–45Fe, austenitic stainless steel, or even a mild steel. The Ni in the butter layer prevents C pickup in the main weld area by dilution.

Braze Welding

Braze welding, sometimes called ''bronze welding'' with cast irons, combines brazing with fusion welding using a bronze filler metal. The process (described in Chapter 10, Section 10.3) is like brazing since little or no melting of the cast-iron substrate occurs with the low-melting bronze alloy filler. Also, the filler is obviously very different from the substrate in composition (i.e., it is heterogeneous). The process is like normal fusion welding in that the joint is filled by melting the consumable bronze filler wire, rod, or electrode in place and not by relying on capillary flow. The advantage of braze welding with cast iron is that only the region immediately around the joint needs to be heated to allow the low-melting filler alloy to melt. This localization of heating, combined with

keeping the level of heating low, minimizes adverse heat effects. The most popular filler used in braze welding cast irons is 39 wt.% Zn/1% wt.% Sn, balance Cu.

Brazing

The brazing of cast irons, like welding, requires special consideration and precautions. Before brazing, the faying surfaces of gray, malleable (ductile), or nodular (spheroidal) cast irons are generally treated by electro-chemical surface cleaning, seared with an oxidizing oxy-fuel gas flame, grit blasted, or chemically cleaned. This is to remove graphite by decarburization, thereby promoting critical wetting. Brazing with silver brazing alloys (i.e., BAg fillers) should be done below 760°C (1,400°F). Copper braze alloys can be used at higher temperatures if heating and cooling are done carefully. It is often desirable to preheat the entire casting during brazing to minimize gradients between the braze area proper and the body of the casting.

11.5 JOINING DISSIMILAR METALS AND ALLOYS

11.5.1 Challenges Posed by Dissimilar Metals and Alloys

Special design requirements sometimes suggest or require that dissimilar metals or alloys should be employed in different, adjoining, or abutting areas of a structure or assembly. Despite the possible dissimilar chemistries and crystal structures of these metals or alloys, a sound structural joint is required. This can be difficult if the different metals or alloys are incompatible chemically or metallurgically, or if they are incompatible in terms of key physical properties like thermal expansion or melting point.

Chemically or metallurgically incompatible materials may not permit intermixing because of mutual insolubility or very limited solubility, resulting in severe macroscopic segregation and gross heterogeneity. Even if intermixing occurs, chemical or metallurgical incompatibilities may result in severe embrittlement upon mixing because of the formation of inherently brittle intermetallic compounds or low-melting eutectics. Finally, there could be an electro-chemical incompatibility that would lead to severe galvanic corrosion in service. Incompatibility (i.e., mismatch of greater than about 15–20%) in coefficient of thermal expansion (CTE) can give rise to severe thermally induced stresses, which, in turn, give rise to severe distortion, residual stresses, cracking, or gross fracture.

Dissimilar metal or alloy combinations are often needed to meet severe environmental demands, such as resisting corrosion (e.g., using cladding), providing wear resistance (e.g., using hard coatings or wear facings), tolerating high temperature (e.g., using oxidation-resisting coatings or thermal diffusion barriers), or providing certain electrical or thermal insulation or conductivity properties. The requirement for successfully joining dissimilar metals or alloys that are chemically or metallurgically incompatible is to prevent or minimize intermixing, or to use intermediate materials (intermediaries) in the joint. The requirement for successfully joining dissimilar metals or alloys with mismatching CTEs is proper joint design and/or use of intermediaries.

Table 11.10 summarizes the challenges posed to joining by dissimilar metals and alloys.

Table 11.10 Challenges Posed to Joining by Dissimilar Metals and Alloys

- Mutual insolubility or very limited solubility
  - -Macrosegregation
  - -Gross heterogeneity
- Severe embrittlement
  - -Formation of inherently brittle intermetallics
  - -Formation of low-melting eutectics
- Electro-chemical (or galvanic) incompatibity leading to corrosion
- Severe mismatch of coefficients of thermal expansion (CTEs)
  - -Severe thermal distortion or warpage
  - -Severe residual stresses
  - -Thermal shock or quench cracking
- Severe mismatch of mechanical properties, which could lead to problems

11.5.2 Avoiding or Minimizing Fusion Welding

There are several options for avoiding or minimizing melting to enable the successful joining of chemically or metallurgically incompatible metals or alloys. First, use mechanical joining methods, employing either fasteners or integral mechanical attachment features. These preclude the need for melting and intermixing and do not alter the chemical composition or microstructure of any joint element. The only potential problems are electro-chemical (i.e., galvanic) incompatibility, which can be handled by using suitable gaskets or coatings, or thermal expansion mismatch, which may be handled by careful joint design or by the use of intermediaries (see Subsection 11.5.3), or both. A second option is to adhesively bond the joint. This could provide suitable joint strength, efficiency, and durability, provided the proper adhesive is selected and proper preparation and application procedures are used. Adhesive bonding precludes the need for intermixing of the substrate materials (i.e., adherends), usually does not alter the chemistry or microstructure of metallic adherends, and can overcome electro-chemical and thermal expansion mismatch incompatibilities by keeping joint elements electrically separated and by providing flexibility or strain compliance in the adhesive. A third approach is to avoid substrate melting and mixing by using brazing or soldering methods. This requires selecting a suitable, mutually compatible braze or solder filler alloy.

If welding is considered necessary for joint strength and serviceability, the amount of melting can be minimized or avoided by using non-fusion welding processes. Examples are friction welding, roll welding, forge welding, flash welding, explosive welding, diffusion welding, and, to a lesser extent, resistance welding (which is actually a fusion process). Brittle intermetallics can still result from some of these processes, either because some melting and mixing really does occur (albeit secondarily to joint formation and/or for a very short period of time over a very small area or volume) or because of interdiffusion. Obviously, electrochemical and CTE compatibility must be acceptable for these processes to work.

11.5.3 Using Intermediate Layers or Intermediaries

Undesirable mixing or gross incompatibilities of physical properties (such as electrochemical potential or coefficient of thermal expansion) can be overcome by separating the two different materials with some intermediate material (an intermediary). This intermediate material, which must obviously be compatible with each and every material that it interconnects, serves to transition or grade (that is, incrementally step) the properties of one joint element to the other by gradually changing the composition and/or pertinent properties. It can also serve as a mutually compatible bridging agent through its compatibility with each joint material.

Intermediaries can take several forms. First, coatings can be used. Metallic or non-metallic (e.g., ceramic or polymeric) coatings can serve to separate or insulate dissimilar metals and alloys from one another or can be used to bridge from one material to the other. Metallic electrolytic (e.g., hard chromium) or electroless plating (e.g., electroless nickel), sputtered coatings, chemically deposited coatings, or clad layers could all be used to transition between metallic joint materials. These layers are usually quite thin, however, and may not tolerate grossly different physical property disparities. Second, interlayers can be used. These metallic layers can have substantial thickness and can be applied by plating, cladding, thermal spraying, fusion welding (e.g., weld cladding or weld surfacing), brazing, etc. One or more interlayers can be used to gradually change the composition and/or properties from one joint element to the other. Finally, transition pieces can be used. These are usually fairly thick and are often welded or brazed or soldered piece by piece, layer by layer. Obviously, each piece in a multiple-step transition must be compatible with the piece materials to which it is joined. The number of transition pieces (or interlayers) depends on how different the two joint base materials are. For CTE mismatch, 10–15% or $1–1.5 \times 10^{-6}$ per °C (or °F) differences between adjoining materials are usually considered reasonable to bridge two different CTE materials. (Again, recall that in the presence of a severe temperature gradient, CTE matching may not be what is needed but, rather, selection of CTEs to minimize the thermally induced stresses caused by the thermal gradient.)

After an intermediary is applied, joining by brazing, soldering, or even welding is then accomplished between one joint component and the intermediary, choosing a suitable filler for that couple. Similar joints are made between abutting pairs of intermediaries, until the entire joint—base element to base element—is bridged. In brazing, the use of intermediaries is called "sandwich brazing." Figure 11.4 shows the use of transition pieces in the weld assembly of automobiles for which the roof, for example, is an aluminum alloy and the lower body support is steel.

Figure 11.5 schematically illustrates a variety of ways of using intermediaries to join dissimilar metals and alloys.

The trick in joining dissimilar metals and alloys is to make the joint components look less different chemically and in terms of physical properties. A similar trick is used for joining dissimilar material types, such as metals to ceramics, metals to glass, and metals to polymers. This is discussed in Chapter 15.

Figure 11.4 The use of transition pieces in the weld assembly of a modern automobile consisting of an aluminum alloy (appearing light in the upper portion of the photograph) roof panel and steel side support frame (appearing dark in the lower portion of the photograph). (Courtesy of Texas Instruments Engineered Materials Solutions, Inc., Attleboro, MA.)

11.6 JOINING INTERMETALLICS

11.6.1 Challenges Posed by Intermetallic Materials

As application opportunities continue to emerge that require materials to perform at higher and higher temperatures for sustained periods of time, traditional construction metals and alloys such as Fe-, Ni-, and Co-base superalloys, reach their usable strength and thermal stability limits. This happens at about 950–1,050°C (1,750–1,925°F) for 1,000 hours at a stress of 150 MPa (22 ksi) for many superalloys, and only slightly higher for some special alloys (e.g., oxide dispersion-strengthened, ODS, superalloys, and Nb-base superalloys) and forms (e.g., cast versus wrought, directionally solidified eutectics, and single crystals versus conventional cast). Admittedly, refractory metals (e.g., W, Mo, and Ta) and their alloys can function at higher temperatures, but their high densities (10.2 g/cm^3 for Mo to 19.3 g/cm^3 for W versus 7.9 g/cm^3 for Fe to 8.9 g/cm^3 for Ni and Co) and attendant lower specific strengths, as well as their higher reactivity, often preclude their use in many applications (e.g., gas turbine components).

There are thus three options for higher temperature service (1) monolithic or reinforced ceramics, (2) graphite or carbon-based (i.e., carbon-matrix and carbon–carbon composites), and (3) monolithic or reinforced intermetallics. Each of these material types has its advantages and shortcomings, but all need to be capable of being joined to enable advanced structures to be produced. Thus, weldability is an especially desirable characteristic. For weldability, intermetallics offer the most promise and so are addressed here. Joining of ceramics, graphite, and ceramic and carbon-matrix composites is discussed in Chapters 12 and 14.

Intermetallics or *intermetallic compounds*, as the name implies, are compounds or alloys with narrow ranges of solubility, composed entirely of metallic elements. Many

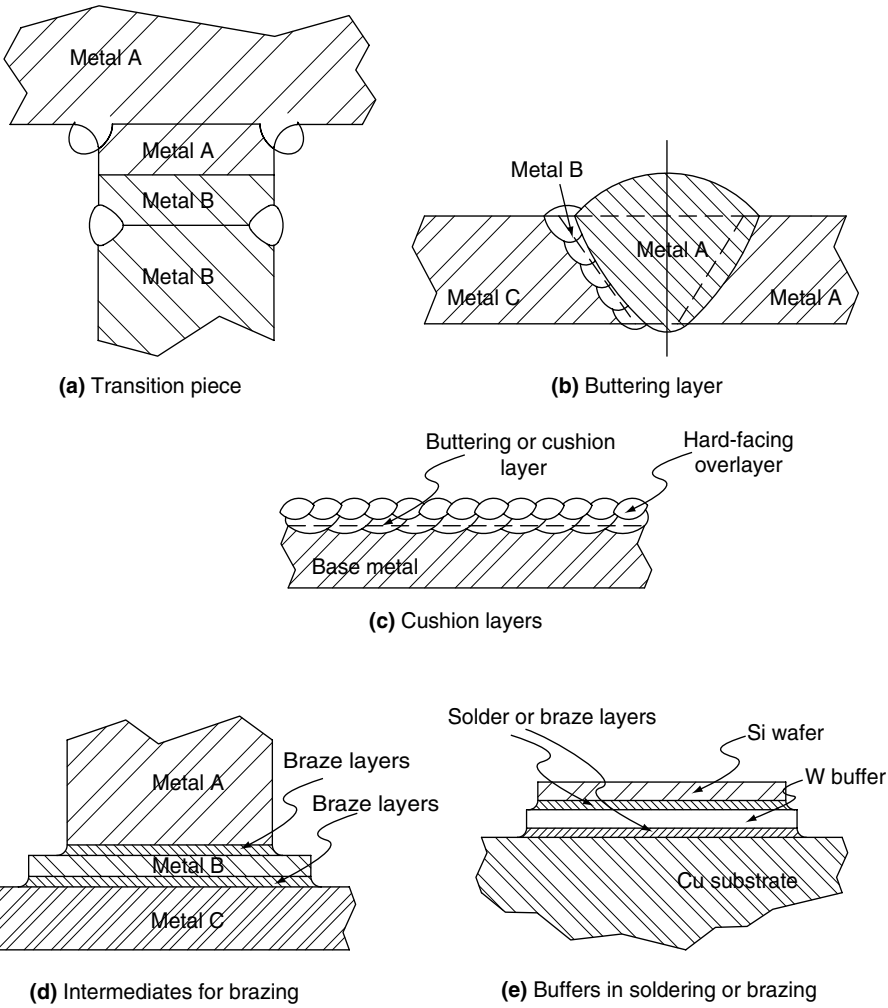

Figure 11.5 Schematic illustration of various techniques for employing intermediate materials and/or pieces for welding, brazing, or soldering dissimilar metals and alloys, including (a) transition pieces (as in Figure 11.4), (b) buttering layers (for reducing weld dilution by the base metal), (c) cushion layers (for absorbing impact loads), (d) intermediates (for brazing), and (e) buffers (for soldering or brazing, to accommodate different CTEs between parts/materials being joined).

intermetallic compounds, such as those formed in brazed or soldered joints at interfaces (e.g., Cu_3Sn), are extremely brittle and have no engineering value. In fact, they are troublesome. There are some intermetallics, however, that are attractive as engineering materials because they are strong, are stable at elevated temperatures, and can be made reasonably ductile by appropriate alloying and/or processing. Some particularly attractive groups of intermetallics are the following:

- Metal (e.g., Fe, Ni, Ti, or refractory metal, Hf) aluminides (e.g., Ni_3Al or NiAl)
- Metal (e.g., Ti, Zr, V, Nb, Ta, Cr, Mo, W) silicides (e.g., $MoSi_2$)
- Metal (e.g., Ti, Zr, V, Nb, Ta, Cr, Mo, W) borides (e.g., TiB or TiB_2)
- Metal (e.g., Fe, Ni, or Co) compounds or long-range ordered alloys with Ti or V (e.g., Fe, Ni]$_3$[V, Ti]).

Some also consider at least some of the metal carbides to be intermetallics, such as SiC. Table 11.11 presents a tabulation of various intermetallics compared to refractory metals and ceramics.

As a group, intermetallics have a narrow range of compositions, based on stoichiometric atomic ratios, and have structures that usually exhibit long-range order by having each atomic species in the compound occupying equivalent sites in the lattice. Thus, intermetallics and long-range ordered (LRO) alloys[10] are a unique class of materials with an atomic arrangement that is distinctly different than that of conventional, disordered alloys. This distinctly different structure gives rise to distinctly different properties.

Below a certain critical ordering temperature, T_c, alloying atoms in LRO alloys arrange themselves on specific, equivalent lattice sites and form an ordered crystal structure. Because this order persists over many, many unit cells, it is called "long-range order." As a result of long-range order, these materials exhibit unique properties because of the effect of that order on atomic mobility and dislocation dynamics. Most significant, the elevated temperature performance of LRO alloys is superior to disordered alloys. The yield strength of many LRO alloys increases rather than decreases with increasing temperature. Elevated temperature creep and fatigue strengths are also high, and many intermetallic materials (like the aluminides) have outstanding corrosion and oxidation resistance. The one shortcoming is a tendency toward brittle behavior in the ordered state, especially at lower temperatures, often below some ductile–brittle transition temperature. This can make fabrication of articles from intermetallics and LRO alloys difficult and can limit structural utility.

There are several intermetallics or LRO alloys that are receiving particular attention now, including studies of their weldability. These include, but are not limited to:

- $(Fe, Ni)_3(V, Ti)$, e.g., $(Fe50Ni50)_3(V98Ti2)$ with a $T_c = 670°C$ (1,238°F)
- $(Fe, Co)_3(V, Ti)$, e.g., $(Fe22Co78)_3(V98Ti2)$ with a $T_c = 950°C$ (1,742°F)
- Ni-aluminides, Ni_3Al, with up to 13% of a ternary addition of Co, Cu, Fe, Ti, or V for improved ductility, or with 0.1 wt.% or 0.5 wt.% Hf for improved ductility
- Ti-aluminides, Ti_3Al, with ternary or quaternary additions of Nb, V, Mo, or W for increased ductility.

The titanium aluminides are particularly interesting because of their inherently lower density (due to their Ti base). Examples of two alloys receiving attention for their weldability are (1) Ti–13.5 wt.% (24 at.%) Al–21.5 wt.% (11 at.%) Nb, and (2) Ti–48 at.% Al–6.5 vol.% TiB_2.

[10] *Long-range ordered alloys*, as opposed to intermetallic compounds, tend to exhibit wider ranges of composition.

Table 11.11 Intermetallic Materials Compared to Refractory Metals and Ceramics

Material	*Melting Temp. °C*	*Density at 20°C g/cm³*	*Modulus GPa*	*Hardness (annealed)*	*UTS at 20°C MPa*	*UTS at Temp. MPa*
Metals						
Tungsten	3,390	19.3	345	450 VN	345–1,400	05X at 600°C
Tantalum	2,996	16.6	189	-	520	520 at 1,000°C
Molybdenum	2,620	10.2	324	200 VN	560	275 at 1000°C
Niobium	2,468	8.6	105	160 VN	275	-
Hafnium	2,230	13.4	138	190 DPH	450	110 at 375°C
Vanadium	1,900	6.0	132	85 R_A	517	-
Zirconium	1,852	6.5	101	180 DPH	344	138 at 315°C
Thorium	1,830	11.7	59	37 VN	218	-
Titanium	1,668	4.5	117	-	235	-
Rhenium	3,167	20.5	465	270 KHN	1,157	-
Osmium	~2,700	22.5	565	800 DPH	-	-
Ruthenium	~2,500	22.4	418	220 VN	540	247 at 1,100°C
Iridium	2,454	12.2	530	170 VN	623	331 at 1,000°C
Rhodium	1,966	12.4	296	135 BHN	958	-
Platinum	1,769	21.4	148	100 VN	124	-
Palladium	1,552	12.0	118	38 VN	145	-
Non-Metals						
Carbon (diamond)	3,550	2.25	1035	>3000VN	1050	-
Carbon (graphite)	3,550	1.30–2.25	8–15	<100 VN	110 (compression)	
Boron	2,030	2.3	390–440	-	3,000–3,500	-
Silicon	1,410	2.4	129–187	-	81.8–130	-

Material	*Melting Temp. °C*	*Max. Use Temp. °C*	*Density at 20°C g/cm³*	*Hardness (VN)*	*Modulus GPa*	*Flexural Strength MPa*
Ceramics						
Aluminum oxide	2,050	1,650	3.92	1,900	360–395	275–550
Amorphous glass	-	-	2.2	600	69	69
Cemented carbide	-	-	17.2	1,600	612	4,000 (comp.)
Concrete	-		2.4	-	25–36	37.2–41.4 (comp.)
Diamond	-	-	2.25	>3,000	1035	1050
Glass ceramics	-	-	2.4–2.7	-	65–120	123–370
Machinable ceramic	-	980	2.5	250	64	344
Magnesium oxide	2,800	-	3.58	-	225	-
Mullite	-	-	2.8	-	145	185
Pyrex glass	-	-	2.23	-	64	69
Quartz	-	-	2.65	-	-	-
Silica, fused	-	-	2.2	-	73	110
Silicon nitride	1,900	1,260	3.2	1,750	200–395	250–1,000
Silicon carbide	2,700	1,260	3.2	2,550	380–430	390–870
Spinel	-	-	3.58	-	260	110–245
Toughened zirconia	2,690	-	6.0	1,300	204	635

(*Continues*)

Table 11.11 (*Continued*)

Material	*Melting Temp. °C*	*Density at 20°C g/cm³*	*Modules GPa*	*Hardness kkg/mm²*	*TYS at 20°C Mpa*	*Nod. at Temp. GPa*
Intermetallics:						
TiAl (γ-Ti)	1,390–1,480	4.0	200	-	250–850	37–40 at 1000°K
Ti-alloys	1,550–1,660	4.5–4.8	110–130	-	400–1,200	18–20 at 850°K
NiAl	1,600–1,640	5.5–5.8	220	-	200–600	28–30 at 1000°K
Ni-alloys	1,400–1,455	8.0–8.4	210	-	150–1,250	20–22 at 850°K
FeAl	1,232–1,31	5.7–5.8	260–280	-	300–600	-
Fe-alloys	1,470–1,550	7.7–7.9	220	-	200–2,000	-
Al-alloys	380–660	2.7–2.9	70–75	-	20–700	-
HfB_2	3,250	11.2	-	-	-	-
ZrB_2	3,040	6.1	-	2,200	-	-
TaB_2	3,000	12.6	-	-	-	-
TiB_2	2,980	4.5	-	3,400	-	-
WB	2,860	16.0	-	9 Mohs	-	-
W_2B	2,770	16.7	-	-	-	-
MoB	2,180	8.8	-	1,570	-	-
MoB_2	2,000	4.3	-	-	-	-
$MoSi_2$	1,870	6.1	-	1,290	-	-
$NbSi_2$	1,950	5.3	-	1,050	-	-
$TiSi_2$	1,540	4.4	-	870	-	-
$ZrSi_2$	1,520	4.9	-	1,030	-	-
$CrSi_2$	1,570	4.4	-	1,150	-	-
WSi_2	2,150	9.3	-	1,090	-	-
$TaSi_2$	2,980	8.8	-	1,560	-	-
VSi_2	1,750	4.7	-	1,090	-	-

11.6.2 Welding Intermetallics

LRO alloys and intermetallics, such as those described above, exhibit a range of weldability, but most have been welded autogenously using GTAW, EBW, and LBW (using pulsed Nd:YAG) with Ar shielding. Inertia friction welding has also been used successfully with the Ti_3Al alloys, as has diffusion welding.

There are two predominant problems in trying to weld the LRO alloys or intermetallics. First, hot cracking tends to occur in some intermetallics in both the heat-affected and fusion zones because of microsegregation of certain phases. Thermal stresses, aggravated by higher welding speeds to keep net heat input down, promote cracking. The tendency toward hot cracking can be lowered by keeping welding speeds below about 13 mm/sec (30 ipm) during EBW of thin sheets of Ti_3Al alloys. Lowering the cooling rate in the HAZ to below 300°K/sec by preheating also has been shown to help. Finally, additions of certain ternary elements, such as 10 at.% Fe to Ni_3Al or 1.7 wt.% Hf to B-doped Ni_3Al, definitely reduces the hot cracking tendency. Second, the loss of long-range order in some alloys has been shown to reduce strength,

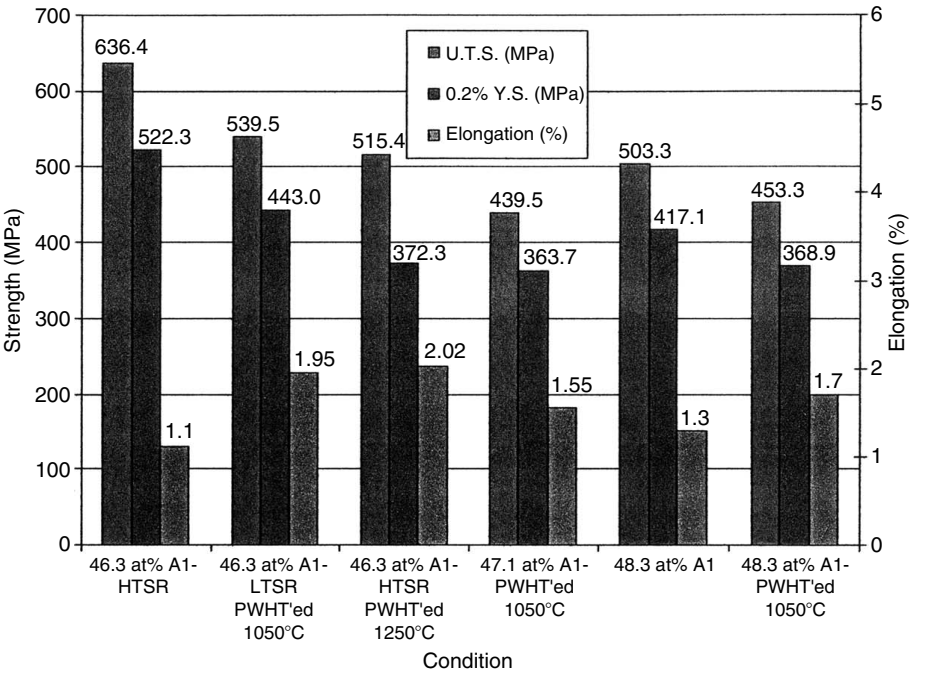

Figure 11.6 Plot of EB weld 0.2% yield and ultimate tensile strengths and elongation for gamma 48Al–2Cr–2Ni Ti intermetallic alloy with slightly different Al contents and various heat treatments. Note: HTSR = high temperature stress relief at 980°C for 2 hours; LTSR = low temperature stress relief at 900°C for 2 hours. (Reprinted from ''Joining of Gamma Titanium Aluminum'', William A. Baeslack, III, AFRL-ML-WP-TR-2003-4036, September 2002, Metals Branch/Metals, Ceramics, and NDE Division/Materials & Manufacturing Directorate, Air Force Research Laboratory, Air Force Materials Command, Wright-Patterson AFB, OH, with permission of W.A. Baeslack, III, Rensselaer Polytechnic Institute, Troy, NY.)

hardness, and ductility in the FZ and HAZ slightly. One example is in $(Fe, Ni)_3(V, Ti)$ LRO alloys. Order can be restored by a post-weld heat treatment if it is essential to obtain optimum properties.

During continued development of LRO alloys and intermetallics, the best way to assess weldability is to conduct continuous cooling studies of their microstructure development and cracking tendency. Such studies are useful for selecting welding processes and parameters expeditiously.

Figure 11.6 shows some properties of welded Ti gamma aluminide plotted versus temperature.

11.6.3 Exothermic Brazing of Intermetallics

The use of an exothermic brazing process known as ''self-propagating high-temperature synthesis'' (SHS) or ''combustion synthesis'' (CS) offers potential for joining refractory

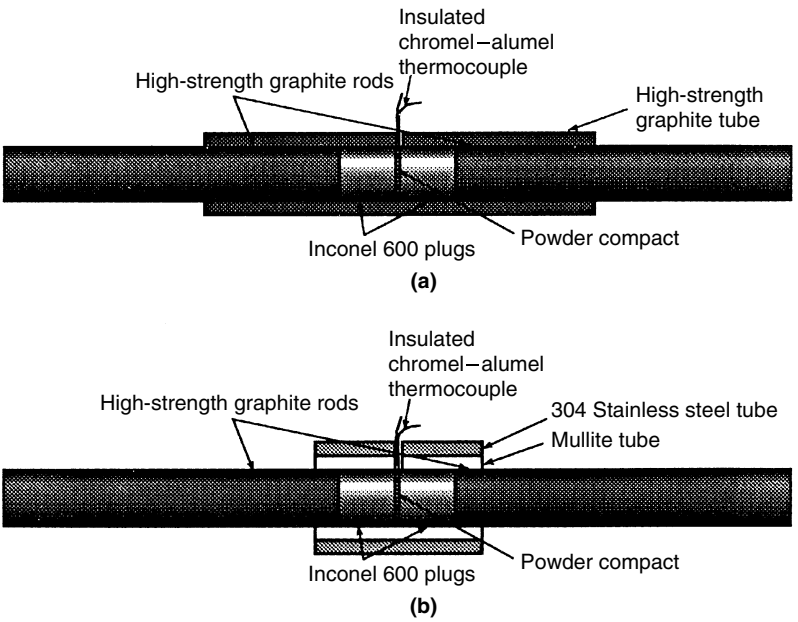

Figure 11.7 Schematic illustration of pressurized SHS or CS for joining intermetallic materials or other hard-to-weld materials. (Reprinted from "Self-propagating high-temperature synthesis (SHS) as a process for joining materials", T.T. Orling and R.W. Messler, Jr., *Welding Journal*, 75(3), 1996, with permission of the American Welding Society, Miami, FL.)

intermetallics. For one thing, joining could be done simultaneously with compound synthesis and even shape production. For another, joint strength would be essentially identical to the substrates. This process is referred to in Chapter 7, Subsection 7.4.8. In the self-propagating mode, the exothermic reaction in a mixture of powdered ingredients (for example, equal atomic percentages of Ni and Al to produce NiAl) is caused to sweep across the reactants as a reaction front. The release of exothermic heat of reaction keeps the reaction going. In the combustion mode, the same mixture of reactants is heated to above a critical temperature, at which point the reaction occurs extremely rapidly, bordering on being explosive. The application of pressure may be necessary to squeeze out gaseous byproducts of the reaction and prevent the formation of porosity in the reaction product, in which case the process is said to be "pressurized" or "pressure-assisted."

Figure 11.7 schematically illustrates how SHS or CS can be caused to join materials, while Figure 11.8 shows an example of the reaction for joining Ni_3Al and a Ni-base superalloy with Ni_3Al by SHS in a Gleeble apparatus (see Chapter 9, Section 9.7.1).

11.7 THERMAL SPRAYING OF METALS, ALLOYS, AND INTERMETALLICS

As described in Chapter 10, it is possible to apply material to a substrate by propelling that material as fine particles in its molten or heat-softened, plastic state at high

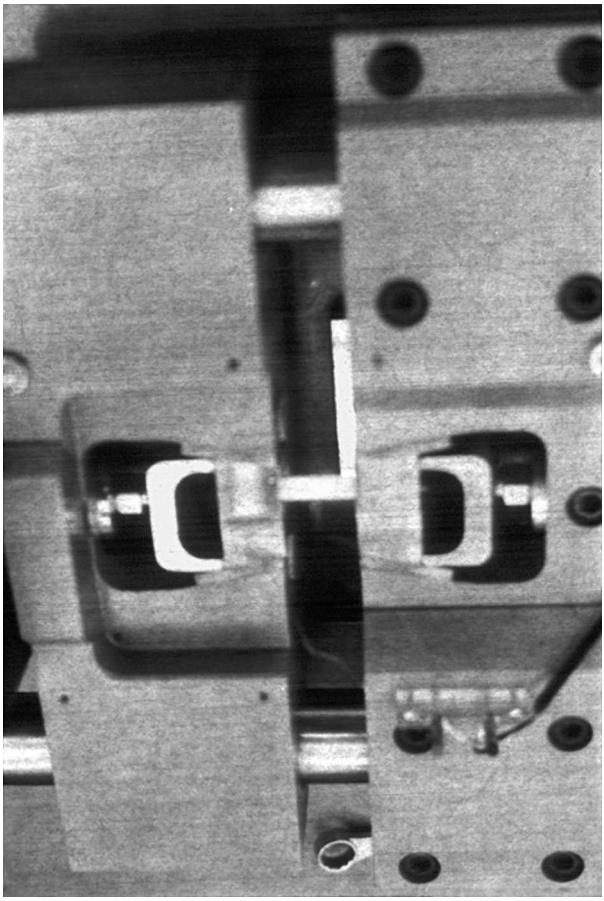

Figure 11.8 The process of pressure-assisted combustion synthesis (CS) exothermic brazing of Ni_3Al to a Ni-base superalloy using Ni_3Al reacted and synthesized in situ. The hot, glowing, resistance-heated cylidrical specimen can be seen between the jaws of the heat-applying device. (Photograph by Robert W. Messler, Jr. at DSI Inc., with permission of DSI Inc.)

velocities, such that when it strikes the substrate it adheres. The process is known as *thermal spraying*. Thermal spraying is a joining process in the sense that it causes one material to unite with another to become a single unit, as opposed to causing one part to join to another. As opposed to producing an assembly of parts, thermal spraying produces an assembly of materials, often a composite.

Metals, their alloys, and intermetallics can all be deposited or joined by thermal spraying. Examples are shown in Table 10.2 of Chapter 10. By thermal spraying, it is possible to restore material lost by wear or corrosion, or to apply a protective layer or coating. Thermal spraying is widely used in the original fabrication and subsequent maintenance and repair of gas turbine blades, vanes, disks, and other components. The resulting adhesion is excellent, often equaling the cohesive strength of the either the substrate itself or, at least, the bulk cast or wrought form of the material being sprayed.

Thermal spraying of metals (often called "metallizing" in the past) can be accomplished using any of four possible methods: (1) combustion flame spraying, (2) electric arc spraying, (3) plasma arc spraying, or (4) detonation flame spraying. The temperature and/or kinetic energy of the particles being sprayed increases in the order in which the processes are listed. Consequently, more refractory metals and alloys, as well as intermetallics (and ceramics), are usually sprayed using either the plasma arc spraying; detonation flame spraying methods are much less common. Regardless of the particular method employed, thermal spraying can be used to deposit a layer of essentially any material on any material, provided there is proper matching of CTEs. Pure metal, alloy, and intermetallic coatings (as well as ceramic coatings) can be applied to pure metals, alloys, or intermetallics or even ceramics in any combination, and/or onto either monolithic or reinforced composite materials. The process is, from this standpoint, extremely versatile.

SUMMARY

Metals and alloys are overwhelmingly the most widely and heavily used materials in the fabrication of assemblies and structures because of their inherently high strength (usually with ductility and/or toughness), and their fabricability by casting, deformation processing, powder consolidation, and machining. Joining of these materials is critically important.

Welding, brazing, and, to a lesser extent, soldering, are used more with metals and alloys than with any other material type because they result in the formation of metallic bonds that offer high joint integrity and continuity of physical (e.g., electrical or thermal conductivity) and mechanical properties. Mechanical joining is actually the most extensively used process for joining metals and alloys, with fastening being more popular than integral mechanical attachment. This is due to the joint properties that can be obtained by a process that changes neither the chemical composition nor the microstructure of the material being joined, and also to the nearly unique fact that mechanical joining processes (almost without exception) allow intentional disassembly without damaging the component parts of the prior assembly. Surely, ease of fastener hole production, ease of fabricating integral attachment features, and good tolerance to bearing loads and inevitable stress concentrations associated with joining at discrete points make mechanical joining of metals and alloys attractive and practical. Although less popular, adhesive bonding is an excellent joining option, especially where light weight and ease of assembly are desired. The load-spreading nature of adhesive bonding is particularly beneficial for joining thin sections. Limited environmental durability is the principal drawback for severe service conditions. Both mechanical joining and adhesive bonding are excellent choices for joining dissimilar metals and alloys provided proper consideration is given to electrochemical and thermal expansion incompatibilities.

Joining of metals and alloys becomes challenging when extremes are involved—either material extremes or geometric extremes, as will be described and discussed in detail in Chapter 15. Material extremes include extreme refractoriness or tolerance of

elevated temperature based on high melting point, extreme reactivity with surroundings and other materials involved in the assembly, and extreme sensitivity to heat arising from low melting point or heat-susceptible microstructures. Geometric extremes include very thin sections, very small components, very thick sections, or very large components. Other extremes are dissimilar chemistries and/or properties and hostile environments, such as outer space or underwater, all of which will be described and discussed in Chapter 15.

For refractory metals and alloys, welding and brazing are preferred, with the major consideration being how to achieve bonding without contamination by pickup of interstitial elements (e.g., C, O, N, H). For fusion-welding processes, achieving the degree of required melting can be difficult, thus favoring high energy density or resistance processes, or forcing use of non-fusion approaches. Adhesives are rarely used because of the severe use-temperature limitations they impose. Mechanical fastening and integral attachment are both viable, but arrangements must be made to allow for potential large expansions and contractions arising from large temperature excursions. For reactive metals and alloys, welding and brazing are again preferred, but exceptional care must be taken to provide adequate shielding from oxygen, nitrogen, hydrogen, and carbon. Mechanical fastening must carefully consider proper matching of the electro-chemical potential of fasteners, while adhesive bonding must carefully consider the possibility of reactions between the inherently reactive adherend and the adhesive. For heat-sensitive metals and alloys, extreme care must be exercised during welding to limit heat input. As a result, inherently lower temperature brazing and soldering, and, especially, adhesive bonding are preferable. While mechanical fastening and integral attachment are fine, care must be taken if heat sensitivity is related to low melting point as low melting point generally leads to mechanical softness and weakness. Examples of heat-sensitive metals and alloys are those with low melting points and those that are strain-hardened, age-hardened, transformation-hardened or hardenable, or extremely brittle and prone to thermal shock.

Dissimilar metals and alloys can be readily joined by adhesive bonding or by mechanical fastening or integral attachment, provided electro-chemical and thermal expansion incompatibilities are properly addressed. Welding, and, to a lesser extent, brazing and soldering, requires consideration of chemical as well as electrochemical and CTE compatibility, both of which can be dealt with through the use of intermediary materials in the form of coatings, interlayers, or transition pieces to bridge the dissimilar joint elements.

Intermetallic compounds and long-range ordered (LRO) alloys, such as aluminides, silicides, borides, and some carbides, and others, are most preferably joined by welding since they are often intended for extreme high temperature service for which their microstructures are inherently well designed. Hot cracking due to inherent low ductility, and loss of long-range order and associated (and desired) properties are the two principal concerns.

Finally, thermal spraying can be used to join surface layers of metals, alloys, or intermetallics to other metals, alloys, or intermetallics, as well as to ceramics in any combination, in both monolithic and reinforced composite forms.

QUESTIONS AND PROBLEMS

1. What properties of metals and alloys make them such attractive materials for use in such diverse and demanding structural applications? Explain your answer.
2. What is the most prevalent method for joining metals and alloys, overall? (Be careful!) Explain why this is probably true. What is the next most popular or prevalent, and surely the highest-performance, process for joining metals and alloys, and why?
3. What are six metallurgical extremes that pose special challenges to the joining of metals and alloys? Explain why each extreme poses a challenge.
4. Name the four most common refractory metals. Name several other much more rare but absolutely refractory metals. Name some borderline refractory metals that melt below 4000°F (2200°C) but above 3000°F (1650°C). Explain why these metals are considered "refractory" from the standpoint of both their production and their use.
5. What are the challenges associated with joining refractory metals and alloys by (a) fusion welding, (b) mechanical fastening, and (c) adhesive bonding?
6. What particular metallurgical problems are presented by the crystal structure of virtually all refractory metals and alloys? Explain why they occur.
7. What processes are typically used to weld the refractory metals and alloys? Explain why each of these is popular. If fillers are used, how are they generally selected?
8. What are the challenges associated with brazing the refractory metals and alloys? Propose some preferred brazing processes for use with refractory metals and alloys. Propose a braze filler for each of the following: (a) W or W alloys, (b) Mo or Mo alloys, (c) Ta or Ta alloys, (d) Hf or Hf alloys. What about for brazing Ir or Ir alloys? (This is a tough one!)
9. Name the three most common reactive metals that are all located in the same region of the periodic table. Name a reactive metal that is located in a very different region of the periodic table. Name some more common metals that are reactive but also heat-sensitive. What causes metals to be classified as "reactive"?
10. What are the special problems associated with welding the reactive metals and their alloys? How do these problems manifest themselves in the final properties of welds? How are these problems resolved?
11. What are the special problems associated with brazing the reactive metals and their alloys? How are these problems resolved by (a) choice of process and (b) choice of filler alloy?
12. Do mechanical fastening and adhesive bonding overcome all of the problems associated with joining the reactive metals and alloys? If not, why not? If so, how so?
13. What is meant by "heat-sensitive" in reference to metals and alloys? Give at least four different problems and explain why each is a problem in (a) fusion welding and (b) mechanical fastening.
14. If fusion welding is used with heat-sensitive alloys, how would you attempt to remediate each of the following problems?

a. Softening in the HAZ of an age-hardened Al–Mg,Si alloy
b. Softening in the HAZ of a strain-hardened Cu–Zn brass alloy
c. Excessive hardening and embrittlement in the HAZ of a medium C mild steel
d. Excessive softening in the HAZ of a quenched and tempered alloy steel

15. What are the five major types of cast irons? Rank these in terms of ease of fusion welding.
16. Why is the joining of cast irons a special challenge? What joining processes would you recommend for high-strength joints?
17. What problems are associated with joining dissimilar metals and alloys? Give one chemically based problem and one physical property–based problem. What are three fundamentally different welding approaches that could be employed successfully, and why?
18. Once they are joined, what are some problems that can still arise with dissimilar metal joints? Give one chemically based problem and one physical property–based problem. Is there any possible mechanical problem? If so, what? If not, why not?
19. What are "intermetallic compounds"? How are these different from "long-range-ordered alloys"? Why are these materials important in modern engineering? What special problems arise in the attempt to join these materials?
20. Why is thermal spraying attractive for applying metals and alloys to the surfaces of metals and alloys? What types of applications (i.e., what problems) require thermal spraying with metals or alloys? How would you recommend spraying an intermetallic material onto a metal?

Bonus Problems:

A. Explain how two diametrically opposed approaches to the fusion welding of gray cast irons both work(namely, (a) preheating the weldment to near red-heat and (b) keeping the weldment as cool as possible throughout welding). What is going on metallurgically that allows each to work?
B. Why is it that adhesive bonding is not used more often in the joining of metals and alloys with extreme properties? Explain your answer thoroughly.

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Chapter 12

Joining of Ceramics and Glasses

12.1 INTRODUCTION

12.1.1 Ceramics and Glasses Defined

Ceramics and glasses, like some metals such as gold, silver, and, to a lesser extent, copper, do occur in a natural state as various minerals. Most, however, are highly refined, if not synthesized, to become what are known as "engineered ceramics" and "engineered glasses." *Engineered ceramics*, as compared to naturally occurring ceramics, are stronger, tougher, and more resistant to corrosion and heat, and offer more unusual and useful electrical, magnetic, and optical properties largely because they are more consistent in chemical composition and more homogeneous in microstructure. Likewise, *engineered glasses*, as compared to naturally occurring glasses, offer better optical, electrical, or other sought-after properties. As materials manipulated by human beings, ceramics and glasses definitely have the longest history,[1] beginning with the use of stone and clay in what was characterized as "the Stone Age." Then clay mixtures, products, and derivatives were developed, followed by refractory oxides such as dolomite (a mixture of magnesium oxide and calcium oxide). Within the last thirty to forty years, so-called "advanced ceramics," arrived, including structural, electronic, superconducting, and magnetic ceramics. Most recently, nanocrystalline ceramics and nanophase-reinforced ceramics have begun to appear, many of them offering unprecedented properties.

It can be difficult to define ceramics because of their variety and diversity. Most generally and least precisely, ceramics are simply solid materials that are not metals or polymers. More specifically and less ambiguously, ceramics are defined as materials composed of nonmetallic, inorganic compounds, singly or in combinations, as mechanical or physical mixtures or as alloys. They can be conveniently divided into two groups: oxides and non-oxides. The oxides are compounds of metallic or metalloid elements (e.g., Si, Ge, Se, B) with oxygen, and include alumina (Al_2O_3), beryllia (BeO), magnesia (MgO), silicon dioxide (SiO_2), thoria (ThO_2), titania (TiO_2), urania (UrO_2), and

[1] The "Stone Age" is the earliest defined period of human culture, characterized by the use of stone tools. It spanned the period from 100,000 B.C. to about 4,000 B.C., although isolated groups of primitive people who utilize only wood, stone, and clay materials have existed until even modern time.

zirconia (ZrO_2), as well as many less common types. The non-oxides are oxidized compounds of one or more metallic elements and one or more nonmetallic elements (one of which could be oxygen), and include, as important examples: carbides (e.g., B_4C, SiC, TiC, WC), borides (e.g., TiB_2, MoB), nitrides (e.g., BN, AlN, Si_3N_4, TiN), sulfides (e.g., ZnS), silicides (e.g., $MoSi_2$, WSi_2, $CrSi_2$), and beryllides (e.g., $ZrBe_{13}$, $MoBe_{12}$), as well as carbonates (e.g., $CaCO_3$, $MgCO_3$), sulfates ($CaSO_4$, Mg, $Al(SO_4)$), titanates (e.g, $BaTiO_4$),[2] and others.

Ceramics and glasses are distinguished from one another based on their methods of processing and their final atomic-level structures. *Ceramics* are nonmetallic, inorganic solids of various compositions that have attained a crystalline state by the firing of crystalline inorganic, nonmetallic starting materials.[3] *Glasses*, on the other hand, are most commonly noncrystalline solids produced by the firing of crystalline inorganic, nonmetallic materials (e.g., oxides, fluorides, borides, nitrides, and silicates). By using fairly recently developed techniques, some glasses (i.e., so-called *glass–ceramics*) can be converted to crystalline ceramics when certain nucleating agents are added to the glass constituents. Thus, glasses are noncrystalline, while ceramics are crystalline. Some practitioners consider glasses a subcategory of ceramics, while others consider them an entirely separate category of materials, since they can, in fact, be produced from base materials that are polymers or metals as well as ceramics.[4]

Because of their atomic-level structure and bonding, ceramics and glasses have many unique properties compared to metals and polymers. Ceramics consist of crystalline arrays of ions or atoms with bonds that are either ionic or covalent or somewhere in between.[5] Bonding is usually very strong and electrons are, for the most part (for either bond type), associated with or "tied" to individual atoms in the crystal. This gives rise to the properties that make ceramics so attractive for so many applications where metals, for example, cannot perform as well or at all. Ceramics have high cohesive strength if microflaws introduced during processing can be avoided.[6] Extremely high hardness can be achieved, up to the $2,800\,kg/mm^2$ (actually 2,550 HV) of silicon carbide, or the $5,000\,kg/mm^2$ of cubic boron nitride (equivalent to over 4,550 HV), or even the $8,000\,kg/mm^2$ of diamond (equivalent to a hardness on the

[2] Compounds consisting of only metallic elements, known as "intermetallic compounds," are sometimes considered ceramics, sometimes metals, and sometimes a distinct and separate material group. In this book, intermetallic compounds are addressed in Chapter 11, Section 11.6, as a separate subgroup of metallic alloys.
[3] Some modern ceramics are produced by other means (i.e., without firing). Example processes are chemical or vapor deposition used in producing silicon carbides, silicon nitrides, and many of the borides.
[4] "Metal glasses" are produced by cooling metals from their molten state extremely rapidly (e.g., faster than 10^6°C/second), to prevent the rearrangement of the metal atoms of the liquid into their preferred crystalline array of a solid. These metal glasses are highly metastable, while other glasses are far less so. Polymer glasses are simply fully amorphous polymers whose development is based primarily on the complexity and bulkiness of the polymer's molecules and secondarily on processing.
[5] Recall that in ionic bonding, valence electrons are actually transferred from one atom (the positively charged cation) to another (the negatively charged anion) to allow each to achieve a stable electron configuration. Bonding occurs by Coulombic or electrostatic attraction. In covalent bonding, pairs or small groups of atoms (of three or four or so) share electrons and, in this way, achieve stable electron configurations, reducing the overall system energy. In mixed ionic–covalent bonding, there is some exchange and some localized sharing.
[6] Because of the existence of "microflaws" in most ceramics produced in practice, compressive strength is usually much higher than tensile strength in these materials.

Vicker's scale of over 8,000 HV, although that scale is not used to that high a level!). The hardest plain carbon and high-strength low-alloy steels have a hardness of 110–240 HV, and hardened tool steels have a hardness of 500–650 HV. Because interatomic bond strengths are so high, ceramics also have high melting temperatures (i.e., they are refractory), have excellent chemical stability (i.e., they have good resistance to corrosion and oxidation because they are already in an oxidized state!), and are usually electrically and thermally insulating (because electrons are tied up in the bonds).

The unique, noncrystalline or amorphous structure of glasses gives them unique properties compared to crystalline ceramics and metals. Bonding within glasses is predominantly covalent or ionic or mixed as in ceramics, or, unlike in ceramics, can be combinations of these from one portion of the glass's network structure to another. Hence, glasses share some properties in common with ceramics but exhibit some different and often unique properties as well. These unique properties arise from the fact that individual atomic species in glasses are not arranged in regular, three-dimensional crystalline arrays, as they are in ceramics, although their arrangement is close to crystalline—exhibiting short-range but no long-range order. Common properties include high strength, especially in compression (again due to the existence of microflaws induced from processing), high hardness, good chemical stability, and, usually, electrical and thermal insulating qualities (i.e., low electrical and thermal conductivity). Unique properties include the absence of a distinct melting point or range (as glasses undergo a continuous softening with increasing temperature, and vice versa), and optical transparency or translucency due to the absence or lesser degree of scattering by periodic charge centers. Other attractive properties of ceramics and glasses include retention of mechanical properties in ceramics (but not in glasses) at high temperatures, low coefficients of thermal expansion (especially in ceramics, and in some glasses), and low density.

The same structures that impart useful properties to these materials, however, impose certain limitations or complications in processing them into useful shapes or, especially, assemblies. For example, ceramics are difficult to melt and cast, are generally impossible to shape by plastic deformation, are almost always difficult to machine, and are difficult to join. Glasses pose some similar as well as some different problems. Both are plagued by their inherent brittleness at normal service temperatures, which hinders fabrication processing and compromises structural integrity under impact loads or concentrated stresses, and both are vulnerable to thermal shock.

As a group, ceramics and glasses fill an extremely important niche in materials engineering because of their exceptional or unique properties compared to metals in particular. For this reason, they are seeing ever-increasing use in both traditional and advanced structural, electronic, magnetic, optical, and emerging opto-electronic applications. Joining ceramics and glasses, therefore, has become a major processing need. However, certain inherent extremes in the properties of these interesting and important materials tend to pose challenges to joining.

Table 12.1 lists the most important applications of ceramic materials by various categories, suggesting a sort of classification scheme. Table 12.2 gives key properties of some major ceramics and glasses compared to some metals.

Table 12.1 Important Applications of Ceramic Materials by Key Classifications

Abrasives
- Synthetic diamond
- Carborundum
- Cemented carbides
- Cermets
- Cutting tools
- Sintered ceramics

Cements
- Portland cements
- High-alumina cements
- Limes, gypsums, and plasters
- Dental cements
- Building materials
- Precast construction units

Engineered Structural Ceramics
- Structural shapes
- Phase-stabilized/toughened ceramics
- Ceramic-matrix composites

Electronic and/or Magnetic Ceramics
- Dielectrics
- Ferroceramics/magnetic ceramics
- Piezoelectric ceramics
- Superconducting ceramics

Refractory Ceramics
- Carbon/graphite
- Oxide ceramics
- Non-oxide ceramics

Structural Clay Products
- Earthenware
- Bricks
- Tiles

Whitewares
- Chinaware
- Enamelware
- Porcelain

Table 12.2 Properties of Some Major Ceramics and Glasses Versus Some Metals for Comparison

Material	*Melting Point (°C)*	*Modulus E (GPa)*	*Hardness (KHN) 100 g*	K_{I_c} $(MPa\sqrt{m})$	*CTE* $(\times 10^6/°C)$	*Resistivity (Ω-cm)*	*Thermal Conductivity (J/s-m.°K) 100°C*	*1000°C*
Alumina-crystals	2050	380	2200	3–5	8–8	$10^{10} - 10^{12}$	30	6.3
porcelain	”	370	”	”	”	”	”	”
sintered	”	370	”	”	”	”	”	”
Beryllia-sintered	2530	310	9.0 MOH	–	9.0	–	219	20
Boron carbide (B_4C)	2350	290	2800	3–4	4.5	0.5	–	–
Boron nitride (BN)	(3000)	83	230	–	–	–	–	–
Borosilicate glass	850	69	–	–	–	10^{13}	–	–
Graphite	3652	–	–	1–2	7.8	–	180	63
Magnesia-sintered	(2800)	210	5.5	3	13.5	10^{13}	38	7.1
Mullite[a]-porcelain	1870	69	–	2–3	5.3	–	5.9	3.8
Silicon carbide (SiC)	2650	340–470	2500	3	4.7	10	–	–
Silicon nitride (Si_3N_4)	1900	–	9.0 MOH	4–5	2.1	–	–	–
Silica glass	1700	72	800	0.5	0.5	$> 10^{14}$	2.0	2.5
Soda glass	700	70	550	0.7–0.8	9.0	–	1.7	–
Thoria (ThO_2)	–	–	640	–	9.2	–	10	2.9
Titanium carbide (TiC)	3250	310	3200	3–4	7.4	$10^2 - 10^3$	25	5.9
Zirconia (stabilized)	2690	150	7.0 MOH	9	6.5	10^{12}	2.0	2.3
Al	660.2	70	–	20–45	23.5	1.5×10^{-6}	221	–
Co	1495	185	–	300	12.3	5×10^{-6}	69	–
Ni	1453	180	–	350	13.3	3.5×10^{-6}	92	–
Steel	1536	200	–	60–140	12.1	10×11^{-6}	75	–
Ti	1668	117	–	55–115	8.4	–	–	–
W	3390	345	–	–	4.5	5.5×10^{-6}	201	–

[a] $3Al_2O_3 \cdot 2SiO_2$

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 433, Table 11.1, 1993, with permission of Elsevier Science, Burlington, MA.

12.1.2 The Special Drivers and Challenges for Joining Ceramics and Glasses

Joining of ceramics and glasses to themselves, to one another, and to other materials (especially metals) is vitally important for many advanced, high-performance applications. These materials are often selected for their unique optical, thermal, electrical, magnetic, chemical, or mechanical properties, but they rarely have the toughness to constitute an entire structure.[7] Therefore, components made from these materials must usually be structurally integrated into an overall system, which is often predominantly of metallic construction.

Ceramic-to-ceramic or glass-to-glass joining is also important for three general reasons (described in Chapter 1). First, joining is needed to overcome processing size limitations. Both physical (i.e., material and facility) and economic constraints in producing ceramics and, to a lesser extent, glasses limit the size of components that can be made. Inherent brittleness in ceramics and glasses leads to the formation of microflaws that degrade tensile properties and toughness in service and can cause gross failure even during processing. This occurs in ceramics at all temperatures and in glasses as they cool to below their so-called "glass transition temperature."[8] Severe thermal gradients and fast cooling rates in these inherently low thermal conductivity materials, either during processing or later on in service, can lead to gross failure through brittle fracture. Thus, fabricating large objects from ceramics or glasses requires the joining of smaller, easier-to-fabricate components.

Second, joining is needed to overcome processing shape limitations. Many ceramic parts, especially those having the most attractive engineering properties, can be made only in relatively simple shapes. This again relates to the inherent susceptibility of these brittle materials to process-induced flaws (e.g., microcracks from shrinkage from various sources, from differential thermal expansion or, especially, contraction, or from thermal shock). Problems are most severe and prevalent at points where section thickness changes occur. Thus, the fabrication of more complex shapes requires machining, which is difficult or impossible because of the inherent high hardness and poor tolerance of point loads and associated stress concentrations. Obviously, joining of simple details into complex units is an attractive alternative.

Third, joining of ceramics and glasses enables material optimization. Some applications require more than one type of ceramic or glass to be combined in the design to obtain the optimum properties desired in the assembly. It is often preferable to have these properties in an integral or unitized component or structure. Thus, joining of dissimilar ceramics or glasses becomes important. Joining of ceramics or glasses to other materials or to ceramics or glasses of different compositions is usually

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[7] Modern so-called "structural ceramics" are being developed to have better toughness, either inherently (i.e., as monolithic materials), or through reinforcement by dispersed particles (including nanoparticles) or second phases, by fibers, or by laminations of other ceramics or materials (e.g., as ceramic-matrix composites).

[8] The "glass transition temperature" found in noncrystalline (amorphous) materials is usually a range of temperatures over which the material's rate of change of specific (i.e., per unit mass) volume with temperature decreases on cooling. In practical terms, it demarcates the change in the material from liquid-like (albeit still viscous) to solid-like (rigid) behavior under applied loading during cooling, with this behavior being reversible.

motivated by technological needs. On the other hand, joining of these materials to make larger or more complex-shaped structures or objects is usually forced by economic considerations in addition to or instead of technological needs.

Figure 12.1 shows how ceramics are commonly joined to produce large, complex structures from smaller, simpler shapes or for producing hybrid structures from ceramics of different compositions. Figure 12.2 illustrates some methods by which ceramics can be joined mechanically, while Figure 12.3 shows how refractory ceramic "firebricks" are actually joined to produce the ceiling of a large industrial furnace. Figure 12.4 shows how glass tubes are joined by flame fusing.

12.1.3 Basic Joining Techniques for Ceramics and Glasses

There are essentially four basic joining techniques used with ceramics and glasses, one exclusively for use during the initial production of the ceramic or glass article and three for use in secondary processing or assembly. The first technique can only be used for joining a ceramic to another ceramic of the same or similar microstructure (even if it is of different composition), while the other three techniques can be used to join ceramics to ceramics, glasses to glasses, or ceramics or glasses to one another or to other materials.

The first technique is *sinter bonding*, a process that is almost exclusively restricted to the joining of ceramics. During the initial production of ceramic articles it is possible, and is often the practice, to join smaller simpler shapes together to form larger and/or more complex shapes by co-firing them. The joint is created by diffusion, often (but not necessarily) during partial melting. Primary chemical bonds of the same type as found in the parent ceramics are formed. The growth of grains (i.e., individual, uniquely oriented crystals in the aggregate) across the initial interface between the abutting pieces obliterates the interface if the process is done properly. This growth is the result of ordinary sintering, in which a small neck forms at a point of localized, intimate contact between particles and grows by diffusion (usually, but not only, in the solid state) to reduce the total surface area and energy. This so-called sinter bonding may require the use of an intermediate material such as a glassy frit or a slurry of the powdered crystalline ceramic or mixed ceramics, or it can occur directly, without the aid of any intermediate material.[9]

The second technique is mechanical joining. It is possible to join ceramics to other ceramics or even to other materials through the use of mechanical interlocking (i.e., designed-in or processed-in physical features) or, to a lesser extent, mechanical fasteners.

The third technique is called "direct joining." It is possible to join ceramics to other ceramics (or glasses to other glasses) by welding, employing either fusion or non-fusion processes. The process is completely analogous to that of metals. In such direct joining no intermediate material is required. This is the most common technique for joining glasses to other glasses of similar or different composition, but it is actually uncommon in the joining of ceramics, where intermediate materials are often required.

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[9] This technique for joining ceramics or glasses during their initial production could be grouped under either the "direct joining" or the "indirect joining" secondary technique (discussed in subsequent paragraphs), depending on how it is actually carried out, i.e., with or without an intermediate material.

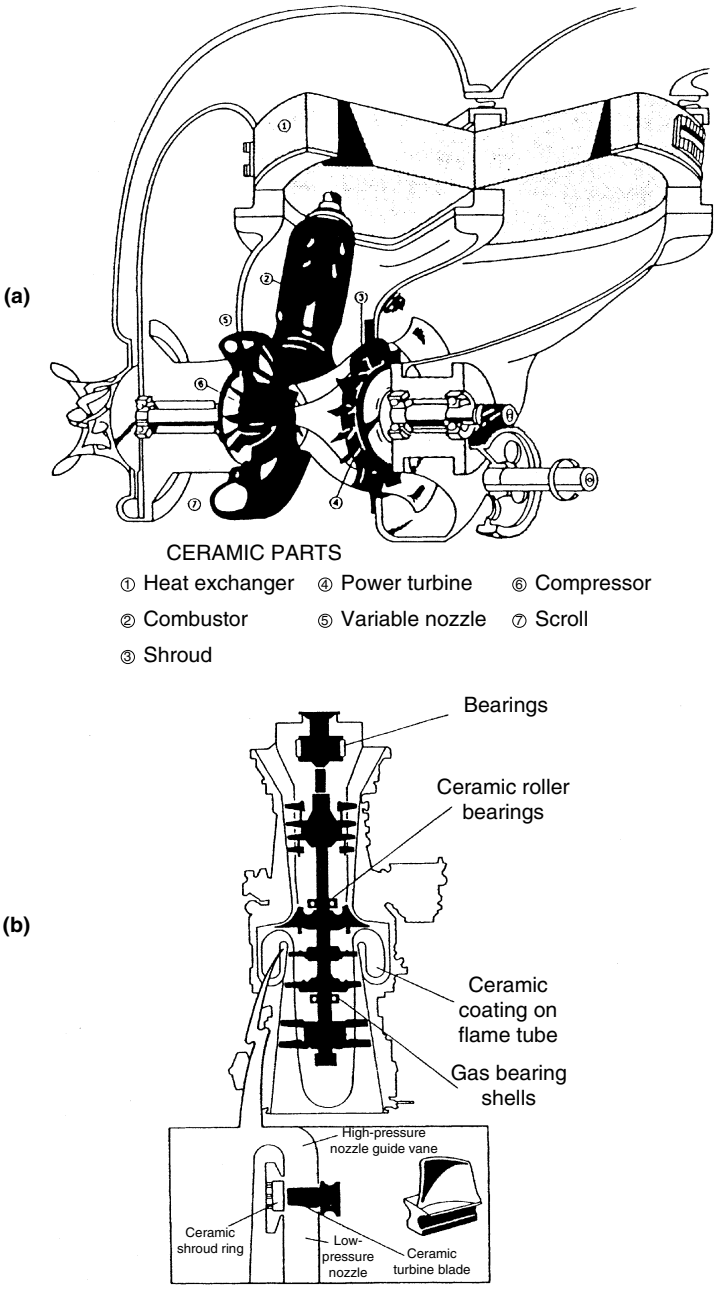

Figure 12.1 Schematic illustration showing the joining of various ceramic components into a complex, high-performance structural assembly, here advanced gas turbines for an automobile (a) and a helicopter (b). (Reprinted from *Ceramic Joining*, M.M. Schwartz, Fig. 7.1, page 167, ASM International, Materials Park, OH, 1990, with permission.)

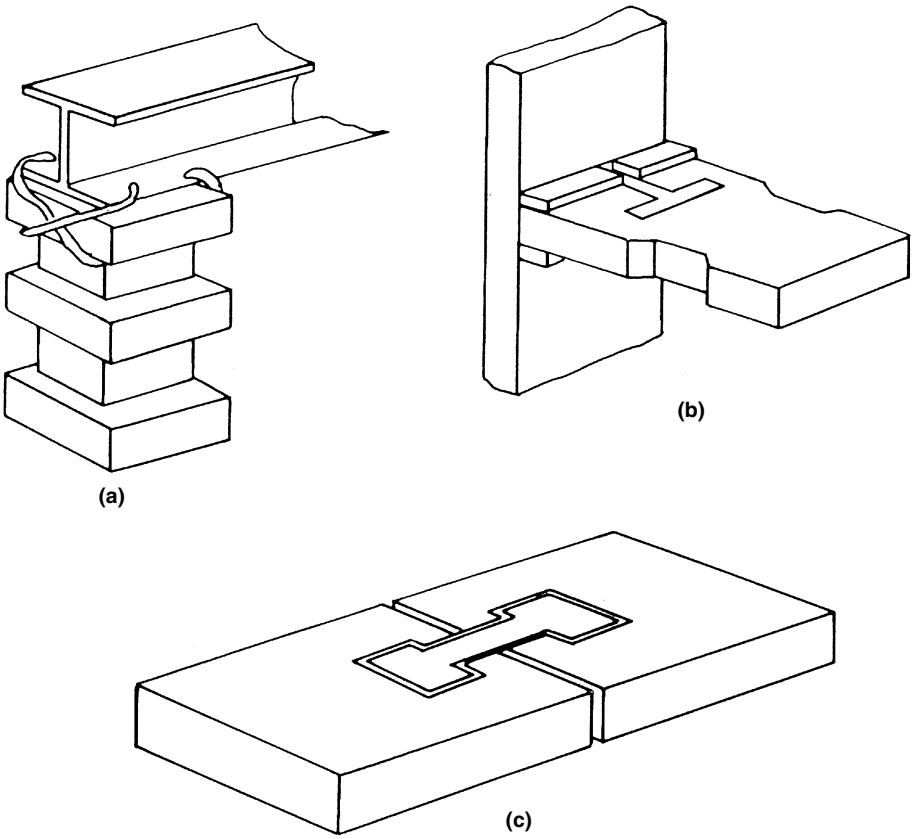

Figure 12.2 Schematic illustrations of some methods for mechanically joining or attaching ceramics to one another or to other materials, especially metals, including (a) wire hangers or brackets, (b) T-pins and slots, and (c) dog-bone connectors. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 12.2, page 438, Butterworth-Heinemann, Stoneham, MA, 1993, with permission.)

The fourth technique involves "indirect joining." This is the most common technique for achieving high-integrity joints between ceramics, between ceramics and glasses, or between ceramics or glasses and other materials. An intermediate bonding material is absolutely required and can be an organic adhesive (in adhesive bonding), glass or glass–ceramic combination (in frits), anhydrous oxide mixture (in cementing or mortaring), a relatively lower melting ceramic (in ceramic brazing), or metal (in metal brazing or soldering, or even in solid state diffusion welding).

Elevated temperature serviceability is often a major factor driving the selection and application of a ceramic. In general, service temperature capability increases for ceramics joined by these processes in the following *ascending* order: organic adhesives, solders, mortars, metal brazes, inorganic cements, ceramic brazes, mechanical fasteners, mechanical interlocks, welding, and sinter bonding.

Figure 12.3 The refractory ceramic brick lining of the ceiling or roof of a large industrial furnace involving the use of metal hangers and dog-bones. The dog-bones are the darker-colored objects immediately at the top of all the light-colored refractory fire-bricks. (Courtesy of Morgan Thermal Ceramics, Augusta, GA, with permission.)

Figure 12.4 The joining of glass components into a complex system using fusion. Here, an oxy-fuel gas flame is being used to heat large-diameter glass tubing to its working point, at which time the tubes are literally fused together with a leak-tight joint. (Courtesy of Corning Glass, Corning, NY, with permission.)

Table 12.3 General Methods for Joining Ceramics and Glasses, Including Cement and Concrete

Direct Joining Methods	
• Sinter bonding:	Exclusive to ceramics, involving co-firing and solid-state, reactive, or transient liquid sintering
• Mechanical joining:	
- mechanical interlocking	Using processed-in shaped features
- mechanical fastening	Using supplemental devices without any intermediate materials
• Welding:	
- solid-phase welding	Autogenous welding using friction
- fusion welding	Autogenous welding by EBW, LBW, PAW, or others
Indirect Joining Methods	
• Mechanical fastening:	Using supplemental devices and intermediate materials (e.g., grommets, gaskets, spacers)
• Adhesive bonding/cementing:	Using organic or inorganic adhesives/inorganic cements (which could result in "direct" joining)
• Brazing:	
- metal brazing	Using a noble or active metal brazing filler or a common metal brazing filler to a metallized surface
- ceramic brazing	Using a ceramic or ceramic+glass brazing filler
• Soldering:	Using an In-based solder or a common solder to a metallized surface
• Welding:	Using an intermediate with either a fusion or a non-fusion welding process
• Wafer bonding:	Similar to reactive brazing, with the development of a low-melting eutectic through diffusion
• SHS or CS welding/brazing:	Exothermic welding or brazing, such that joining could be direct (homogeneous weld) or indirect (heterogeneous weld or braze)

In the following sections, the joining of ceramics to ceramics will be treated first, and then the joining of glasses to other glasses will be treated. Many of the techniques apply to both. The joining of ceramics or glasses to other materials (e.g., metals) is treated in Chapter 15.

Table 12.3 lists some general methods for joining ceramics (including cement and concrete) and glasses.

12.2 MECHANICAL JOINING OF CERAMICS

12.2.1 Characteristics of the Mechanical Joining Process

Mechanical joining, as seen in Chapters 2 and 3, is basically quite simple and efficient, and should, in principle, be capable of producing reasonably high-strength joints that can

even tolerate sustained high temperatures. The characteristic lack of ductility in ceramics and glasses until quite high temperatures are reached, however, severely limits the temperature range over which this method of joining is applicable. The severe stress concentrations that can arise in the body of the ceramic or glass components from discrete points of fastening or attachment can lead to catastrophic failure by fracture.

In mechanical joining, applications involving tensile loads, grommets, or shims of soft material (e.g., soft metals like lead, copper, aluminum, or nickel) can be used to minimize stress concentrations by distributing the load and preventing damage to the ceramic's surface. Flow (by creep) of such metals, however, limits the stresses that can be supported. High compressive loads can usually be better tolerated than tensile loads, and considerable care must be taken to avoid the development of tensile loads caused by bending or other complex loading situations. Localized loading under the heads or feet of fasteners should be distributed by employing washers capable of conforming to the surface of the ceramic or glass.

Widely different coefficients of thermal expansion (CTEs) between ceramics (which have low CTEs) and metals (which have high CTEs) must be carefully considered to avoid the development of thermally induced stresses during what are often large temperature excursions, given that ceramics are often chosen for their refractoriness. Four strategies to address this are as follows: (1) mechanical connectors or fasteners must be selected to minimize differences in CTEs; (2) the connectors or fasteners themselves must be designed to flex to accommodate strains; (3) softening grommets or shims must be used; or (4) the joint must be designed in such a way as to allow slippage to accommodate any mismatch.

12.2.2 Mechanical Joining Methods

Despite the limitations just described, a variety of methods can be used to join ceramics mechanically to themselves or (as will be seen in Chapter 15, Subsection 15.3.3) to other materials. Examples include (1) mechanical interlocking (using various tongues-and-grooves with generous radii to avoid stress concentration, or interlocking ceramic pieces such as "dog-bones," etc.); (2) press or shrink fits (for close tolerance assemblies) that develop compressive residuals in the ceramic that must be overcome before applied tensile loads give rise to tensile stresses; (3) metal hangers, brackets, or clamps that allow some "play" or slip to accommodate strain mismatches; (4) mechanical fasteners (e.g., bolts, screws, pins); and (5) integral threads on or in the body of the ceramic or glass part. Some of these techniques are shown schematically in Figures 12.2 and 12.5.

It should be noted that, as with refractory metals and alloys, the major problem in mechanically joining ceramics is accommodating large dimensional changes caused by thermal expansion and contraction over wide excursions of temperature during initial processing or in service. For this reason, mechanical interlocking schemes as well as schemes using fasteners must be able to accommodate these occasionally large strains and associated movements. One approach is to use loose-fitting joints with built in "play" or "slop." Another approach is to design the joint and the mechanical interlock or fastener to allow slip. These are called "slip joints" or "expansion joints"

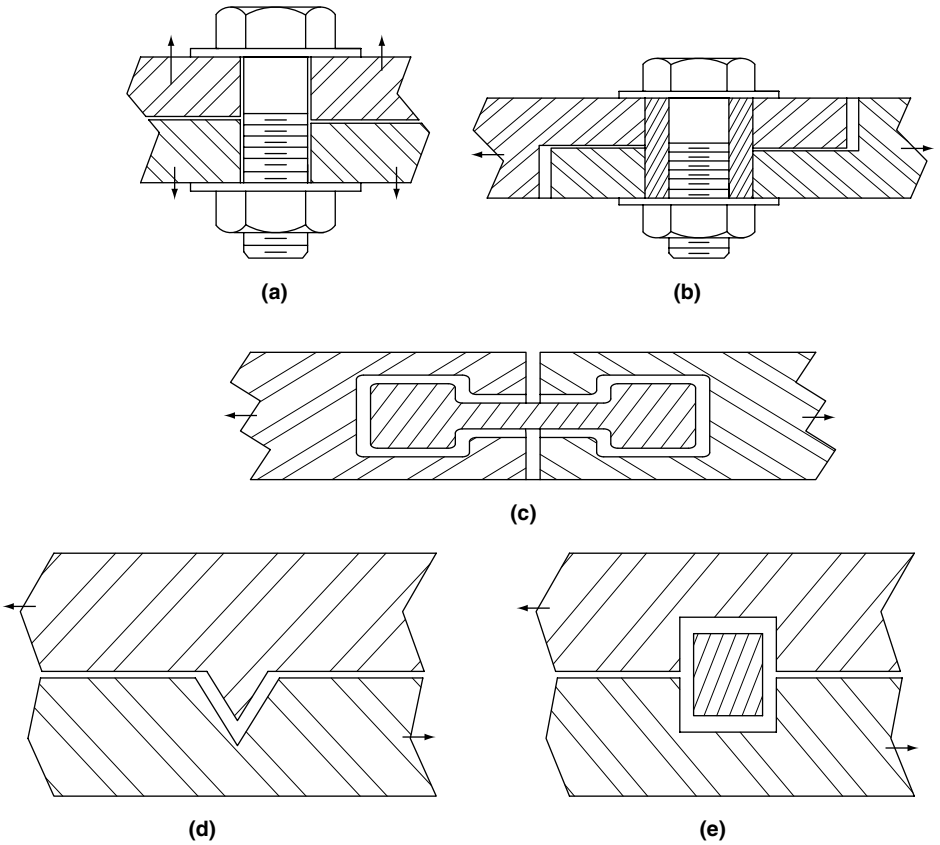

Figure 12.5 Schematic illustration of various mechanical joining methods suitable to ceramics, including nuts and bolts employing oversized metal washers (a), metal washers and metal sleeves (b), metal or ceramic dog-bone connectors (c), various shaped rigid interlocking features (d), or grooves and inserts analogous to keys and keyways (e).

and are similar in concept to the joints used on roadways over bridges or in railroad track rails, where expansion and contraction from normal weather-induced temperature changes can cause gross movements between large-dimension components. Some examples of slip joints are loose-fitting keyed joints (e.g., tongues-and-grooves or "dog-bones" and recesses), slotted (versus round) fastener holes to allow movement in at least one direction, spring-loaded interlocks or fasteners to take up one-dimensional changes, and inherently flexible joints such as ball-and-socket types. Mechanical fasteners must be used carefully to avoid excessive point or concentrated loading in bearing and to avoid further aggravating stress-concentration effects. Tensile loads are best kept low at all costs.

Figure 12.6 shows how precast concrete blocks with mechanical interlocks that are part of their geometry can be used to erect retaining walls.

Figure 12.6 Interlocking precast concrete blocks making up a retaining wall. The interlocking features are at the upper and lower horizontal faces of the blocks. (Courtesy of the International Masonry Institute, Albany, NY, with permission.)

12.3 ADHESIVE BONDING, CEMENTING, AND RELATED JOINING OF CERAMICS

12.3.1 Adhesive Bonding or Joining of Ceramics

The *indirect joining* of ceramics with either organic-based materials (e.g., organic, polymeric, and elastomeric adhesives) or inorganic-based materials (i.e., predominantly cements and mortars) is one of the simplest and most widely used methods for joining ceramics to other ceramics (including various cements and concretes). Clearly, with cement and concrete representing approximately 40–50% of all the material (at least on a tonnage basis) used in the world each year, cementing and mortaring are particularly widely used. These processes offer manufacturing advantages of low cost, high speed, and simplicity (i.e., relatively low skill compared to many other joining processes). They offer two more very important mechanical advantages: (1) adhesives distribute applied loads, thereby minimizing potentially destructive stress concentrations; and (2) most adhesives (at least the organic types) can accommodate significant strains without significant development of stress in the ceramic substrate. The exceptions are cement and mortar, which, like the material they are used to join, have high moduli and poor ductility and toughness. Hence, at least some of the joints in structures joined by cement or mortar have strain-accommodating "expansion joints" consisting of some type of flexible material insert (e.g., rubber).

Despite these advantages, two serious shortcomings are associated with organic adhesives. First, the strengths of organic adhesives, and especially strain-accommodating sealants (e.g., elastomers, which are generally non-structural adhesive types) are low. While true structural adhesives can achieve strengths of 35 MPa (5,000 psi), sealants and elastomers are commonly an order of magnitude weaker. This may not be a particular problem if the total loading in tension or shear is low, or if sufficient bond area is available to allow the imposed stress to be sufficiently low. Second, the service temperature for organic adhesive (and many inorganic cement) bonded assemblies is severely limited compared to what most ceramics can tolerate. Organic

Table 12.4 Some Important Adhesives for Use With Ceramics or Glasses

Adhesives for Ceramics		
Epoxies	2nd Generation acrylics	Polysulfides
Inorganic adhesives	Inorganic cements	Mortars
Adhesives for Glasses[*]		
Polyvinyl butyral	Phenolic butyral	Nitrile-phenolic
Neoprene	Polysulfide	Silicone
Vinyl acetate	Epoxies	

[*] It may be necessary, depending on the application, to select a transparent form of these adhesives.

adhesives can typically tolerate only a couple of hundred degrees Celsius, while the useful service temperature for most ceramics can be several thousand degrees Celsius. Typical masonry cements and mortars can tolerate temperatures somewhat higher than their organic counterparts, to approximately 260°C (about 500°F) or even slightly higher for short periods of time, but these, too, degrade when the "waters of hydration" that bond the various ceramic particles comprising the cement or mortar break down. Thus, organic adhesives are normally used to join ceramics when special wear or electrical properties are needed, but not when elevated-temperature service is required. For the much higher service temperatures tolerated by refractory ceramics, special refractory cements are employed (e.g., high alumina cement).

Organic (polymeric) adhesives for use with ceramics (or glasses) include polyvinyl butyral, phenolic butyral, neoprene, polysulfide, silicone, vinyl acetate, epoxies (normally with 200°C or 400°F limits), and epoxies modified with elastomers. For high temperatures (e.g., 300°C or 575°F), polyimides, polysulfones, polyphenylquinoxalines, and polytriazines are used. One important application of organic adhesives is for joining glasses to one another or to metals, as in forward-facing windows in commercial aircraft.

Table 12.4 lists some adhesives used with ceramics.

12.3.2 Cement and Mortar Joining of Ceramics (Including Cement and Concrete)

As stated before, concrete is a major construction material. The annual tonnage of concrete produced in the U.S. (as but one example for industrialized countries) is greater than that of all metals, other ceramics, and polymers combined! The reasons for its popularity are (1) the exceptional flexibility in design and form it offers to the designer; (2) the ability to pour it in place at room temperature, even underwater; (3) its low cost compared to virtually every other engineered structural material; and (4) its suitability for producing massive structures requiring huge volumes of material (e.g., dams). While concrete's compressive strength is high (typically 5,000–10,000 psi or 35 to 70 Mpa at room temperature after full curing for 28 days), its tensile strength (as for most ceramics) is low, as are its ductility and toughness. Resistance to typical environmental conditions (i.e., from weather or underwater) is very good. One of concrete's great drawbacks is

that the strength of its hydraulic bond cannot be tested in advance (as it can for steel, for example); it depends on the skill (and integrity!) of the contractor.

As described earlier (in Chapter 5, Subsection 5.3.9 and Section 5.5), concrete is a mixture of ingredients, composed of a "paste" or binder (a matrix in composite material terms) and an "aggregate" (a reinforcing phase in composite material terms). The paste, referred to as the cement, is most commonly composed of Portland cement, water, sand, and sometimes entrained air, while the aggregate is typically a fine gravel (i.e., less than 1/4 in. or 6.35 mm) or coarse gravel (i.e., larger than 1/4 in. or 6.35 mm) of small whole or crushed stones normally making up 60–75% of the total volume of the mixture. The Portland cement (itself a mixture of tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) in various proportions, depending on ASTM Grade as shown in Table 5.7) is mixed with approximately six times its volume of sand and enough water to give the cement the consistency desired. The cement mix hardens by a hydration reaction with the formation of a gel[10] and embedded crystals. For optimum, fully cured strength (which occurs after 28 days), water purity must be kept within established limits (set by the Portland Cement Association), the aggregate must be controlled for size, shape, porosity, specific gravity, moisture absorption, resistance to freeze–thaw cycles, strength, resistance to abrasion, and chemical stability. Entrained air (used to improve the workability of the concrete and to increase resistance to freeze–thaw cycles) must be controlled to between 3% and 9% by volume by using a resin added to the concrete. Other additions can be made to the preceding mix to impart certain working or service properties, including (1) *accelerators* (such as calcium chloride) to decrease the setting time at low temperatures; (2) *retarders* and/or *water-reducing agents* (such as lignosulfonate, a byproduct of wood pulp) to increase the setting time in very hot weather; and (3) *superplasticizers* (typically sulfonated condensates) that increase the workability or flowability of the concrete while keeping water-to-cement ratios lower for higher set strength.

Figure 12.7 shows plots of the typical compressive strengths for air-entrained and non-air-entrained concretes as related to curing time.

The joints employed in construction with cement and/or concrete rely on mechanical interlocking as well as on chemical bonding through hydration. Such interlocks can be the result of geometric features placed in precast structural elements, such as blocks or larger structural modules (e.g., floor sections, beams, etc.) or of preplaced, cast-in reinforcing bars or meshes, normally of steel. Examples of common joints used in cement, mortar, and concrete construction are shown schematically in Figure 4.21.

In addition to the use of Portland cements, various concrete mixes, and various mortars in masonry construction, there are many other demands for joining so-called "structural" or "advanced" ceramics that call for the use of cements and mortars with special formulations and properties. Cement- and mortar-type interlayers are widely used for the simple and relatively inexpensive indirect joining of ceramics to one another. In this context, "cements" and "mortars" are inorganic materials consisting of various

[10] A *gel* is a solid network with entrapped liquid. Hence, it is critical that cement not be allowed to dry during setting or curing. It must continuously be covered with some water so that the setting reaction is not stopped prematurely.

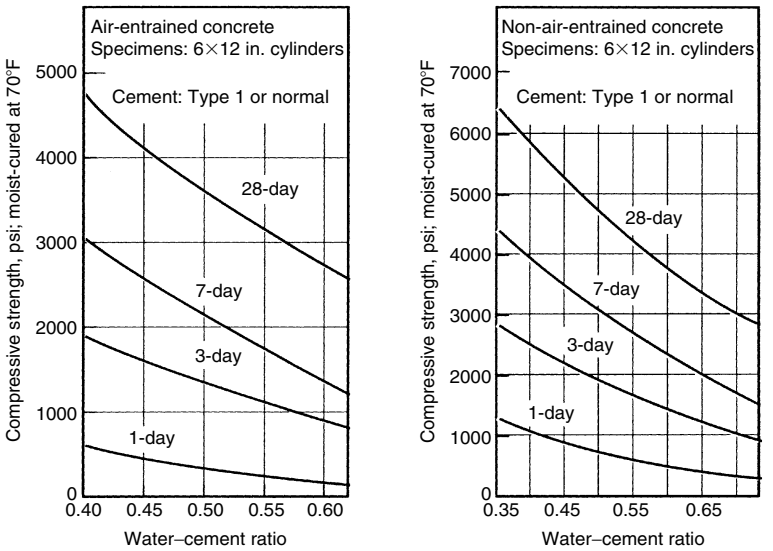

Figure 12.7 Plot of the typical compressive strengths of air-entrained (left) and non-air-entrained (right) concrete after various curing times. (Reprinted from *Engineering Materials and Their Applications*, 4th edition, R.A. Flinn and P.K. Trojan, Fig. 17.3, page 687, Houghton Mifflin Company, Boston, MA, 1990, with permission.)

mixtures of glasses, glasses and crystalline ceramics, or just crystalline ceramics. They are generically classified as "inorganic adhesives."

Cementing and mortaring are also known generically as "ceramic sealing" or "ceramic seal bonding." As a group, cements and mortars for these purposes offer higher temperature serviceability than organic adhesives and normal construction cements and mortars. They offer most of the advantage of load spreading but little or none of the strain accommodation offered by their organic counterparts. However, the strengths of these cements and mortars can be substantially lower than the strengths of normal (e.g., organic) adhesives.

Cements and mortars of this type fall into two broad categories: (1) unfired ceramic cements and (2) fired ceramic cements. The *unfired ceramic cements* and mortars offer good bonding and insulating (thermal and electrical) and sealing capabilities from room temperature to temperatures approaching the use temperatures of refractory ceramics. As stated previously, they are basically inorganic and provide good bond strength, good corrosion resistance, and electrical and thermal insulation. There are three basic types of unfired cements: (1) hydraulic set (of which masonry cements and mortars are a major subtype), (2) air set, and (3) chemical set.

Hydraulic set cements, as has been described for Portland cement in Chapter 5 and in this chapter, contain various anhydrous compounds that react with water to form hydrated compounds and bonded aggregates. The major types are Portland cement, calcium aluminate, natural lime–silica, and combinations thereof. Portland cement functions to about 260°C (500°F), while calcium–aluminate is a more refrac-

tory mortar with serviceability to around 1,000°C (1,850°F) and even higher. *Air set cements* are inorganic compounds, often mixed oxides, and are blended with water and sodium or potassium silicate. Setting occurs by evaporation of the water, and service temperatures for cementing applications approach 1,100°C (2,000°F). The *chemical set cements* involve a broad range of chemical reactions but predominantly acid–alkali types to form gels. Various siliceous compounds as well as phosphates, chlorides, and sulfates are used. With all these types, shrinkage can be 1–5% and must be accommodated by design and processing.

Fired ceramic cements include (1) vitreous ceramic sealants compounded of glasses and other ceramic materials that form glasses on firing, and (2) crystalline ceramic sealants including recrystallized glasses and crystalline compounds that contain little or no glassy phase. Both of these materials require high maturing temperatures for joining shapes but offer excellent refractoriness. Service temperature capability is excellent.

Table 5.8 lists the properties of some important unfired and fired ceramic cements and mortars.

Several issues must be considered with cements and mortars. First, thermal expansion mismatch between the cement or mortar and the ceramic substrate can be an important factor limiting service temperature. This must be taken into account during the design of the joint, usually with the addition of some form of "slip joint" or "expansion joint." Second, thermal decomposition of the cement or mortar (e.g., lime-based mortars) can be a problem. This decomposition is usually what limits service temperature. Third, chemical interaction between the cement or mortar and the ceramic substrate can cause problems. Degradation of joint strength is most common, but degradation of the base ceramic can also occur. One possible reaction is a eutectic reaction that can result in the formation of a low-melting constituent that compromises the structural integrity of the joint and structure. Fourth, unfired ceramic sealants may not provide hermeticity, as they tend to be porous and permeable to gases.

Cements and mortars are typically selected to have compositions that are similar to the ceramics they are to bond. An excellent reference is "Cementitious Bonding in Ceramic Fabrication," by J.F. Wygant, in *Ceramic Fabrication Processes,* by W.D. Kingery, MIT Press, Cambridge, MA, 1958.

12.4 BRAZING AND SOLDERING OF CERAMICS

12.4.1 Challenges Posed by Ceramics to Brazing and Soldering

As defined in Chapters 7 and 8, and by the American Welding Society, brazing and soldering are joining processes that create atomic-level bonds and adhesion through the capillary flow of molten fillers between properly set up and gapped solid substrates. Brazing refers to those processes that are carried out with fillers that melt and flow above 450°C (840°F), while soldering refers to those processes that are carried out with fillers that melt and flow below 450°C (840°F). Based on this definition, brazing and soldering represent an entirely different approach to the indirect joining of ceramics using metal intermediary materials in most cases (e.g., metal brazing or soldering) or

ceramic, glassy-ceramic, or glass intermediary materials in other cases (e.g., ceramic brazing or soldering with "solder glasses").

The major challenge posed by ceramics (as well as glasses) to brazing and soldering relates to the chemical stability of these two closely related materials. By being chemically stable, inert, or non-reactive, ceramics and glasses tend to resist being wetted by other materials, especially molten metals. Without wetting of the substrate by molten metal filler, it is impossible to form strong "metallurgical-quality" joints. A sound brazed or soldered joint can be produced only if some type of filler can be found that wets a ceramic or a glass, or some method is developed to cause traditional (e.g., metal) fillers to wet the ceramic or glass. Even when wetting and subsequent bonding are achieved, there are problems with the inherent incompatibilities in certain physical properties between metal fillers and ceramics (or glasses) that must be dealt with, the most notable being mismatched CTEs. If CTE differences are too great (generally greater than 10% to 15%), induced stresses can become intolerable, leading to failure along or immediately adjacent to the joint in a weak boundary layer.

As a result of these characteristics of ceramics and glasses, a number of brazing and soldering processes for ceramics apply a metal layer to the ceramic, in what is often referred to as "metallizing." Subsequent brazing or soldering is used to join one metallized ceramic or glass to another metallized ceramic or glass.

12.4.2 Characteristics of Brazing Methods for Ceramics

There are fundamentally two general methods for brazing ceramics (virtually identically analogous to soldering): (1) those that use metallic materials as the intermediary material, called "metal brazing," and (2) those that use ceramic materials as the intermediary, called "ceramic brazing." The soldering analogues are simply metal soldering of metallized ceramics (or glasses[11]) and soldering of glasses (and possibly some glass-containing ceramics), using what is known as a "solder glass," which is just a low-melting glass intermediary. These will be described and discussed in Section 12.8.

For *metal brazing*, there are three specific methods that are not necessarily fundamentally different in terms of the mechanism of bonding or adhesion but are differentiated by practice. These are (1) noble metal brazing, (2) active metal brazing, and (3) refractory metal brazing. *Metal brazing* of ceramics is one of the most common methods of joining ceramics (excluding cements and concretes, where it is never used!), especially for high-performance applications. The basic advantage of metal brazing is that a variety of materials can be joined together by generally simple procedures, producing vacuum-tight joints that have modest to high strength.

For *ceramic brazing*, the ceramic filler actually fuses or melts and distributes in the joint by capillary action. This distinguishes it from ceramic cementing with fired cements, where no such overt melting and certainly no capillary flow occur. Rather, the cement to be fired is preplaced in the joint to be bonded by firing. An advantage of

[11] As will be seen in Subsection 12.8.4, indium- (In)-based solders do wet glasses, as well as virtually all ceramics and metals.

ceramic brazing over metal brazing is the closer match of properties between the filler and the substrates, especially physical properties like CTE.

12.4.3 Metal Brazing of Ceramics

The obvious problem in trying to braze or solder ceramic substrates is achieving wetting by the molten filler. When metal filler is used, the problem is overcome either by altering the surface of the ceramic to make it like (or make it act like) a metal, or by getting the filler to act like a ceramic. The aforementioned three major methods of brazing ceramics using a metal filler or intermediate layer are described in more detail in this section. It can be seen that in noble metal brazing and in one form of active metal brazing, the filler metal is made to act like a ceramic by having one or more of its components oxidize. In another form of active metal brazing and in refractory metal brazing, the surface of the ceramic is chemically altered by the metallic braze filler to act like a metal. By metallizing the surface of the ceramic (at least in the area to be joined) by depositing or embedding metal by electroplating, sputtering, ion-implanting, or some other means, brazing with a metal filler can be accomplished as is normally done with metal substrates, that is, by simply selecting a filler that is compatible with the metallized surface material.

Noble Metal Brazing

Noble metal brazes are most commonly based with silver or platinum and their alloys, somewhat less often based with copper or nickel, and occasionally based with other noble metals (e.g., palladium and gold). Such brazing is normally done in air or even an oxygen-rich atmosphere, with evidence that noble metal oxides form and bond with the ceramic substrates, particularly oxide ceramics. Typical ceramics that have been brazed with Pt, Pd, Au, or Ag, with little or no pressure beyond that needed to hold joint elements in contact, include MgO, Al_2O_3, ZrO_2, UO_2, BeO, ferrite, SiO_2, glasses, and graphite.[12]

Noble metal brazed joints have strengths that are approximately 50–100% of the strength of epoxy bonded joints, their strengths can be much greater for some fillers. Strengths range from 23 MPa (3,400 psi) for lead as the filler to 252 MPa (36,000 psi) for Pt in Al_2O_3.

Active Metal Brazing

Active metal brazing is most commonly based on the use of Ti but can also be based on Zr, Nb, Cr, or Y, particularly for Al_2O_3. Iron, cobalt, and nickel have also been used with certain oxide ceramics. Two procedures have been used with traditional Ti-based active metal brazing. In the first, the Ti (or other active metal) is incorporated into the brazing alloy to aid wetting by forming an oxide and another compound (e.g., carbide, boride) through reaction of the active metal with the ceramic. In the second, the

[12] Graphite is an allotropic form of carbon with a layered arrangement of covalently bonded C in which layers are held together by van der Waal's bonds. Some consider it a ceramic, while others do not. In this book, the joining of graphite is discussed in Chapter 14, and under the heading "Active Metal Brazing" above.

surface of the ceramic to be brazed is coated with the active metal or a compound that decomposes to that metal (e.g., a metal hydride, such as TiH_2). In this second approach, done in vacuum, the metal layer is referred to as "metallization." This layer is then wet by an appropriate metal braze alloy for use with the active metallization.

Another method of applying active metals (per Pattee *et al.*, 1968) is to use molten alkali halide salts (e.g., alkali or alkaline earth halides for Ti) to prevent oxidation while the active metal is deposited on the ceramic substrate. In a diffusion-brazing approach, brazing is accomplished below the liquidus temperature of the braze filler alloy, through the formation of a transient liquid phase.

For graphite, a particularly difficult material to join by any means, Ag–Cr, Ag–Ti, Ag–Zr, Au–Zr, and Cu–Cr filler alloys work well by forming carbides with the active metal component. Two commercially available braze fillers usable with graphite are 68.8 wt.% Ag/26.7 wt.% Cu/4.5 wt.% Ti (with a melting range of 830–850°C or 1,525–1,560°F) and 70 wt.% Ti/15 wt.% Cu/15 wt.% Ni (with a melting range of 910–960°C or 1,670–1,760°F). Because graphite reacts readily with oxygen, oxygen must be excluded, usually by brazing under a vacuum of approximately 10^{-4} Torr. The reaction of an active component and subsequent diffusion are common means for achieving wetting and bonding when brazing substrates that are difficult to wet.

Refractory Metal Brazing

Although some brazing is actually done using refractory metals and their alloys (e.g., Al_2O_3 or Si_3N_4 to themselves using Nb or Zr, respectively), these materials are usually used to coat or "metallize" a ceramic, with subsequent brazing to the metallized layer (often with a second metal applied by plating). Tungsten and molybdenum are normally used as the refractory metal metallization. The process requires high temperatures (e.g., 1,400–1,600°C or 2,600–2,900°F) and a hydrogen atmosphere. The refractoriness of the resultant braze, along with high strength and reliability, make this an attractive option, especially for Al_2O_3 and BeO. Strengths are typically 105–150 MPa (15,000–30,000 psi) for Mo brazing of Al_2O_3 at 1,500–1,600°C (2,750–2,900°F).

The operative refractory metal needed to metallize the ceramic's surface can be embedded as a powder during initial processing, mixed with the parent ceramic and fired to develop a coating, chemically or vapor deposited, or sputtered on. Another common method of metallizing with a refractory is called the "molybdenum–manganese (Mo–Mn) process." Here, a paint of molybdenum and manganese metal powder or their oxides is applied to the ceramic as a slurry. The assembly is fired in hydrogen with a controlled dew point so that the manganese is converted to its oxide (MnO) while the molybdenum remains a metal. The MnO then reacts with the ceramic grains and any glass phase to form a controlled amount of glassy phase containing the MnO. The Mo sinters to form a porous coating into which the glassy phase penetrates and interlocks mechanically. In addition, the glass at the interface reacts with the Mo to form MoO, thus forming a chemical bond to the ceramic grains since they are compatible. An electrodeposited coating (e.g., Ni) is often plated over this metallized

layer to further facilitate brazing. Alumina and beryllia substrates have been metallized this way using either Mo with Mn or W with Mn.

12.4.4 Ceramic Brazing of Ceramics

Ceramics can be joined to themselves (or, as will be seen in Chapter 15, to metals) by brazing with ceramic fillers or intermediate materials instead of metals. Glasses are common ceramic braze filler materials, but mixtures of glasses and crystalline phases, or of all crystalline phases (often as eutectics) can be used. Ceramic brazes can be applied and processed in the same fashion as metal brazes (i.e., in the solid state by diffusion brazing, or in the fluid or liquid state by conventional brazing). While ceramic brazes tend to be preplaced before brazing rather than applied during brazing, they do distribute uniformly within the joint by capillary action, as all brazes must by definition.

Ceramic brazes provide good environmental compatibility (e.g., service temperature and corrosion and oxidation resistance), often better than most metals. Unfortunately, ceramic brazes tend to be less tolerant of thermal expansion mismatch than most metal brazes, so care must be exercised in their selection and use and in the joint's design. One common ceramic braze filler is Pb–Zn borosilicate glass. Some refractory ceramic brazes are manganese pyrophosphate and MnO eutectic (30:70), $Al_2O_3-MnO-SiO_2$ for Al_2O_3, and $Al_2O_3-CaO-MgO-SiO_2$ for Al_2O_3.

Normally, ceramic brazing is accomplished using the furnace brazing method with appropriate atmosphere control, which may include a vacuum.

Soldering of ceramics to one another or to metals typically employs metallized layers applied by powder processing (during ceramic production), by chemical or physical deposition, by electro- or electroless plating, by sputtering or ion-implantation, or by other means. Soldering is then a matter of finding a compatible solder for the metallized layer and for the intended functional requirements and service conditions. The other alternative is to use In-based solders (see Chapter 8, Subsection 8.5.10).

12.5 WELDING OF CERAMICS

12.5.1 Challenges Posed to Welding by Ceramics

Welding is really the oldest technique for joining a major group of ceramics, namely silicate glasses. The joining of two or more glass shapes to one another in the practice of glass working, although not usually referred to as such, is actually welding. Welding of ceramics, in general, and very refractory, single-phase crystalline ceramic materials, in particular, is relatively new.

The basic requirements for welding ceramics are twofold. First, the ceramics involved in the joint must be chemically compatible with each other and with the environment in which they will be joined. Second, the ceramics being joined must be mechanically compatible (i.e., have reasonably comparable strengths) and physically compatible (i.e., have coefficients of thermal expansion that differ by no more than approximately

$1-1.5 \times 10^{-6}$ per °C). The two general methods for welding ceramics are (1) in the solid state using non-fusion processes, and (2) using melting with fusion processes.

12.5.2 Solid-Phase (Non-Fusion) Welding of Ceramics

Solid-state, solid-phase, or non-fusion welding is accomplished by heating the components to be joined while they are held in intimate contact, usually under substantial pressure. For metals, which are often inherently ductile, this pressure causes plastic deformation of microscopic surface asperities or localized points of contact, bringing more points into contact. With more points of intimate contact, there are more paths for solid-state diffusion. Filler is rarely needed or used. For ceramics, on the other hand, such plastic deformation is difficult or impossible because of the inherent hardness and brittleness of most ceramics. Only limited elastic deformation is able to contribute to increasing the number of points of contact for subsequent diffusion, and these are usually not sufficient to allow enough diffusion in reasonable lengths of time. Thus, in the solid-state welding of ceramics, an intervening layer of ceramic in powdered form is often sandwiched between the joint components. This powder can be of the same composition as the similar substrates being joined, or of one or the other or a mixture of both if the two materials being joined are of different compositions. In extreme cases, where the two materials being joined are chemically or physically incompatible, a series of thin layers of powder, grading from one base material's composition to the other's composition, can be used. Figure 12.8 schematically illustrates such a functionally gradient material (or FGM) joint.

Bonding during solid-phase welding and/or by sintering occurs by the creation and growth of a reaction zone between the two materials to be joined, both of which rely on diffusion. When dissimilar materials are being joined, bonding will usually depend on the reaction and/or interdiffusion of both joint component materials. With similar materials, it depends primarily on the sintering ability of the materials (i.e., the rates of diffusion as well as pressure-induced recrystallization and grain growth). The principal process used for accomplishing solid-phase welding of ceramics to ceramics is diffusion welding, in the form of hot pressing and isostatic pressing. The process of diffusion welding for ceramics is essentially identical to that for metals (Chapter 6, Subsection 6). However, it is usually much slower because of the inherent difficulties

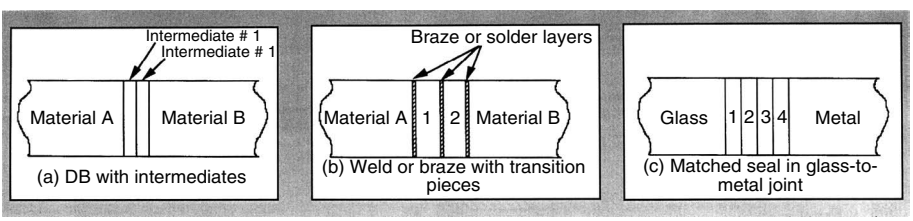

Figure 12.8 Schematic illustration of a functionally gradient material (FGM) joint between two different materials.

posed to diffusion in ionic compounds (where both small cations and an appropriate number of large anions must both diffuse to maintain a balanced electrical state). Various friction-welding processes have also been successfully employed to join ceramics, but not without great challenges to equipment and to process control. For both diffusion and friction-welding, ductile metal interlayers ("intermediates") can be used to advantage, provided any inherent chemical incompatibilities can be overcome by either metallizing the ceramic or oxidizing the intermediate layer.

A wide variety of oxide and non-oxide ceramics have been solid-phase welded to themselves, to one another, and to metals. Table 12.5 summarizes solid-phase welding of oxide and non-oxide ceramics. Figure 12.9 shows an example of ceramic welding by the friction-welding process.

12.5.3 Fusion Welding of Ceramics

As with metals, fusion welding of ceramics is achieved by filling the joint between parts to be joined with molten material obtained by melting the edges of the parts making up the joint while they are in contact (i.e., in autogenous welding), or with additional molten material from a filler of a similar or compatible material. In fusion welding of dissimilar materials, their melts must also be compatible with one another. Besides chemical compatibility between substrates and any filler, the ceramics being fusion-welded must be compatible with the welding environment and must be physically compatible with one another.

While compatibility with the welding environment depends somewhat on the particular fusion technique being used, an overall requirement is that the ceramics melt properly and then solidify properly. There are several problems associated with attempting to fusion-weld ceramics. First, most ceramics have very high melting temperatures, so getting enough energy into them to cause them to heat enough to melt is not a trivial matter. One method is to employ processes with high energy densities. Second, some ceramics (e.g., BN, Si_3N_4, and SiC) vaporize without melting (i.e., they sublime), so at normal pressures they cannot be fusion welded. This problem can only be overcome by employing a non-fusion technique. Third, some ceramics (e.g., MgO) have very high vapor pressures at the melting points, so they vaporize after they melt, making fusion welding difficult, if not impossible. This problem can also be overcome by employing a non-fusion welding process. Fourth, the very high temperatures involved in the fusion of many ceramics can cause problems with phase transformations in surrounding heat-affected areas, leading to severe property degradation or fracture. Again, non-fusion welding, with as little elevation of temperature as possible, is the only answer. Fifth, thermal stress fractures, resulting from severe temperature gradients around the fusion zone or from thermal shock on heating or cooling, have long been considered a major obstacle to the fusion welding of ceramics. Supplemental heating around the intended weld, to reduce thermal gradients and stresses, helps greatly, although non-fusion welding is certainly a viable alternative. Other problems arise from the fact that most ceramics are electrically non-conductive, so they cannot be made part of the circuit for arc welding or resistance welding.

Table 12.5 Summary of Successful Solid-Phase Welding Methods for Oxide and Non-Oxide Ceramics

Materials Welded	*Type*	*Temperature (°C)*	*Pressure (1000 psi)*	*Time (min.)*	*Ambient Weld Strengths (1000 psi)*
Oxide					
MgO–MgO	C to C	1750–1950	3–5	5	7–17
$Al_2O_3-Al_2O_3$	C to C C to P P to P	1700	1	30–40	–
$Al_2O_3-Al_2O_3$	C to C	1900–2000	0.1–1	60–70	–
$Al_2O_3-Al_2O_3$, Al_2O_3 + 1 wt-% MgO	C to C	1400	2	60	–
Al_2O_3 + 1 wt-% MgO					
$Al_2O_3-Al_2O_3$	C to C	1600	0.6	180	–
$Al_2O_3-Al_2O_3$	P to P	–	–	–	up to 54
$Al_2O_3-Al_2O_3$	P to P	1300–1400	8–10	20–30	30–45
$Al_2O_3-Al_2O_3$	P to P	1500	0.7	60	–
$Al_2O_3-Al_2O_3 + H_3PO_4$ or AlF_3	P to P	900–1200	0.7	60	20–50 estimated
NiO–NiO	P to P	1000	10	90	–
MgO–MgO	P to P	800–1100	10–12	30	1–15
MgO–MgO	P to P	1300–1400	5	15	–
CaO–CaO (with 2 wt-% LiF)	P to P	1000–1100	5	15	–
CeO_2-CeO_2	P to P	1000	–	–	–
Al_2O_3-Nb	P to P	–	–	–	up to 11.7
Al_2O_3-Cu	P to P	1000	0.3	10	10–28
Al_2O_3–Ni, Fe, etc.	P to P	1250–1300	0.3	10	7–28
Al_2O_3-Ni	C or P to P	1200	–	–	–
Al_2O_3-Nb	P to P	1500	2.1	17	11–13
Al_2O_3–ZrC, ZrN, or ZrB_2	P to P	1750	3	60	–
ZrO_2 or ZrB_2	P to P	1800	3	60	–
Nonoxide					
LiF–LiF	C to C	840–860	0		
B_4C-Si					
TaC–TaC	P to P				
(ZrC, NbC, TaC)-(Nb, Ta, Mo, W)	P to P	1200–2000	0.7	5–60	
$ZrC-ZrB_2$					
$ZrN-ZrB_2$	P to P	2100	4	30	
ZrC–ZrN					
$TiC-TiB_2$					
TiC–TiN					
TiB_2-TiN	P to P	2100	4	60	
$TiC-ZrB_2$					
C–C	P to P				

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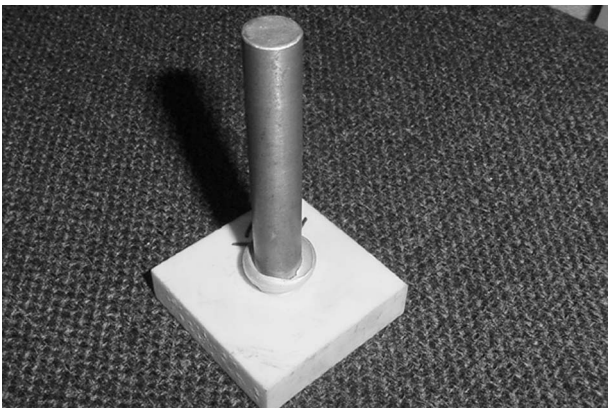

Figure 12.9 An example of a friction-welded ceramic assembly. (Courtesy of the Edison Welding Institute, Columbus, OH, with permission.)

Table 12.6 Summary of Successfully Fusion-Welded Ceramics and Ceramic Combinations

Welded Parts	*Weld Method*	*Representative Weld[a] Strengths Achieved (1000 psi)*
$Al_2O_3-Al_2O_3$	Electron beam	15–30
Al_2O_3-Ta	Electron beam	5–10
$Al_2O_3-Al_2O_3$	Laser	25
ZrB_2-ZrB_2	Arc	20–60
TaC–TaC	Arc	20–30
ZrB_2 + C or SiC to itself	Arc	$\sim$ 10
W–graphite	Arc	3–5
ZrB_2–Mo, Nb, or Ta	Arc	15–30
ZrB_2 + SiC–Mo or Ta	Arc	15–30
ZrB_2–graphite	Arc	$\sim$ 2
Fireclay, brick to itself	Arc (with feed material)	0.2–1.5

[a]These strengths generally represent only preliminary trials and may often be limited by the quality of the bodies to be welded.

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Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 449, Table 12.4, 1993, with permission of Elsevier Science, Burlington, MA.

The principal processes for fusion welding ceramics, in descending order of popularity, are (1) laser beam welding (LBW) (primarily CO_2 but also Nd:YAG), (2) electron beam welding (EBW), and (3) arc welding (especially GTAW and PAW), provided the ceramic will support the establishment of an arc. LBW and EBW can be employed with any ceramic that will melt without subliming or thermally decomposing. PAW can be employed on even insulating ceramics by using a non-transferred arc technique. Table 12.6 summarizes the successful use of fusion-welding processes with various ceramics and ceramic combinations.

12.6 OTHER METHODS FOR JOINING CERAMICS TO CERAMICS

12.6.1 Wafer Bonding of Ceramics

As described in Chapter 6, Subsection 6.2.2, the tendency for atoms to bond is the fundamental basis for welding, and it was said that all that is necessary for two atomically clean and perfectly flat and smooth materials to join is that they be brought into contact. Perhaps this statement was accepted with skepticism, but there is a process that proves this to not only be true but have practical significance. It is *wafer bonding*.

Wafer bonding, also termed "direct bonding," relies on the phenomenon that mirror-polished, flat, and atomically clean wafers of almost any material, when brought into contact at room temperature (or at higher temperatures), are locally attracted to each other by van der Waal's forces and adhere and bond to each other. After starting the process by locally applying a slight pressure to the wafer pair, the bonded area spreads laterally over the whole wafer area in a matter of a few seconds. Since the bonding achieved at room temperature is typically relatively weak, room temperature-bonded pairs usually are subjected to heat treatment to strengthen the bonds across the bonding interface. Wafer bonding has begun to emerge as a technology of choice for joining materials in various areas of microelectronics and micro-electro-mechanical systems (MEMS). It has been successfully applied with wafers of silicon, as well as a variety of compound semiconductors (e.g., GaAs), and appears to offer great potential for the fabrication of opto-electronic devices. It is also extremely attractive for joining single-crystal layers to single-crystal substrates, when normal epitaxial growth methods prove difficult or impractical. The keys to the successful execution of the process are clearly proper mechanical preparation for flatness and smoothness, and proper chemical preparation for smoothness and cleanliness. The process of wafer bonding is described by Gösele *et al.* (2000).

Figure 12.10 shows a schematic of the steps involved in the wafer-bonding process.

12.6.2 Sinter Bonding of Ceramics

Most materials that are produced by powder techniques, such as most refractory materials (whether metals, ceramics, or intermetallics), require more than simple pressure compacting of the powder particles to result in strong particle-to-particle bonding as well as high density (i.e., low porosity). They usually also require sintering. Sintering is the process of causing particles of a material (or more than one material) to join together by interdiffusion. The driving goal of sintering to join two particles is to reduce their total surface area and, thus, surface energy. The necessary diffusion can occur entirely in the solid phase or can involve the liquid phase, which can drastically accelerate the process. It is possible and quite common to take advantage of the process of sintering to join smaller ceramic parts into a larger and often more complex-shaped unit. This process is called "sinter bonding."

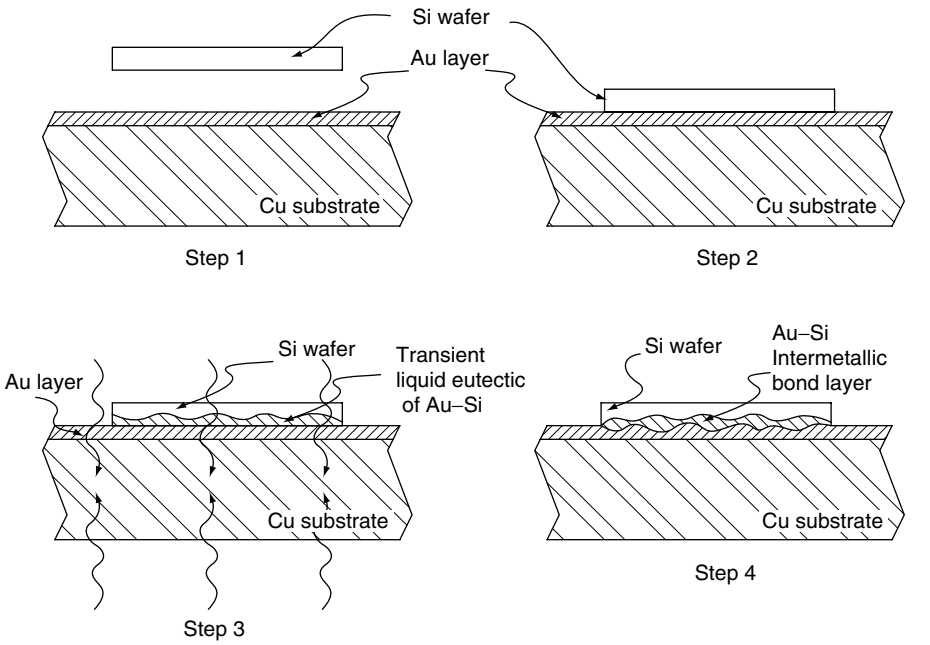

Figure 12.10 Schematic illustration showing the steps involved in wafer bonding.

Sinter bonding tends to be almost exclusively restricted to the joining of ceramics, even though it is possible with metals. The reason is that the process is quite natural for ceramics, which are often synthesized into even the simplest forms by powder processing, including sintering. It is thus an integral step in ceramic part production already. Again, the joints between small parts are created by diffusion, often, but not necessarily, during partial melting. Primary chemical bonds of the same type as found in the parent ceramics (i.e., ionic or covalent or mixed) are formed. The growth of grains (i.e., individual, uniquely oriented crystals in the aggregate) across the initial interface between the abutting pieces obliterates the interface if the process is done properly. This so-called sinter bonding can occur directly, without the aid of any intermediate material such as a glassy frit or a slurry of the powdered crystalline ceramic or mixed ceramics, or may require the use of such an intermediate material.[13]

Figure 12.11 schematically illustrates how sinter bonding joins ceramic parts during their co-sintering.

[13] As stated in footnote 9, this technique for joining ceramics or glasses during their initial production could be grouped under either the "direct joining" or the "indirect joining" category of secondary techniques. It depends on how it is actually carried out (i.e., without or with an intermediate material).

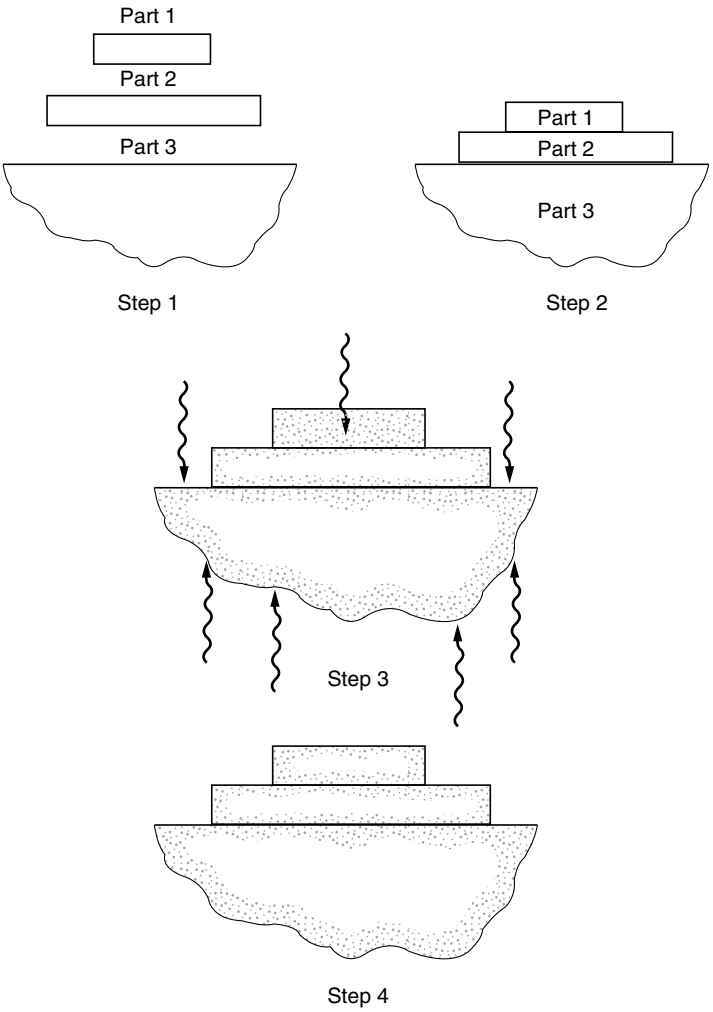

Figure 12.11 Schematic illustration showing the steps involved in sinter bonding.

12.6.3 SHS or CS Welding or Brazing of Ceramics

Self-propagating high-temperature synthesis (SHS) and *combustion synthesis* (CS) are two modes of an exothermic brazing process (see Chapter 7, Subsection 7.4.8, and Chapter 11, Subsection 11.6.3). They differ in that SHS occurs progressively as a reaction front sweeps through the volume of powdered reactants, while CS occurs all at once (often with near explosiveness). The processes are capable of creating joints by causing the reactions to occur *in situ* between joint elements. To work, the appropriate reactants are packed between the solid joint elements, the entire sandwich assembly is held under unidirectional squeezing pressure, and the reaction is triggered.

(Such reactants are often a powdered elemental metal and an oxide, as in the aluminothermic reaction between powdered Al and powdered Fe_3O_4 that underlies the thermite welding process.) Once complete, the newly formed product phase bonds one joint element to the other. As examples, Ni_3Al can be bonded to Ni_3Al by causing powdered Ni and Al to react *in situ* to produce a Ni_3Al bonding layer, or two pieces of graphite can be joined by reacting powdered Ti and graphite *in situ* to form a bonding layer of TiC. While not widely used yet with ceramics, the processes of pressure-assisted SHS and CS offer potential.

Figure 11.8 shows the SHS process in operation in a Gleeble apparatus.

12.7 COMPARISON OF JOINING TECHNIQUES FOR CERAMICS

Because of the fundamental difficulties encountered in trying to join structural or advanced ceramics (beyond masonry using cement and concrete), it is worth reviewing the various options as well as their relative merits. Table 12.7 gives a summary comparison of the various methods.

Briefly, the primary advantage of organic adhesive bonding, inorganic cementing or mortaring, and, to some extent, mechanical joining using fasteners or various integral attachments is their ease, versatility, and low cost. Their strength is good; it is often comparable to that of brazing and soldering. Temperature capability is extremely limited for organic adhesives, is better for water-set inorganic cements and mortars, and is still better for air-set and chemically-set inorganic cements and mortars. Serviceability for mechanically fastened ceramics depends on the fastener material, while for

Table 12.7 Comparison Among Various Methods for Joining Ceramics

					Welding	
Requirement	*Adhesive*	*Cement*	*Mechanical*	*Brazing*	*Diffusion*	*Fusion*
Strength (numbers in 1000 psi)	Low, e.q. < 5	Usually low, often below 1	Low–medium, e.g., 1–10	Good, e.g., 10–40	Often best, e.g., 20−60+	Good, e.g., 10–50
Compatibility with severe environments	Generally poor[a]	Poor–medium	Poor–medium	Medium–good	Medium–good	Generally best
Vacuum tight	Questionable[b]	Generally not	Generally not	Usually	Frequently[c]	Usually
Cost	Low	Low	Low–medium	Medium–high	Medium–high	Low–high[d]

[a]e.g., due to temperature and some chemical limitations.
[b]e.g., due to outgassing of organic constituents.
[c]May not always be as reliable as brazing or fusion welding.
[d]Can depend substantially on the number of parts, material, and type of weld, (e.g., would be low for considerable arc welding but would be high for small numbers of electron beam welds).
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integral attachment it can be as good as the ceramic itself. Sealing, for hermeticity, can be a problem with porous, unfired ceramic cements, but can be excellent for fired cements. Low stress, low temperature service for all of these methods is good.

Brazing, especially with active metal-type fillers, is most widely used for demanding applications, with great potential for exothermic brazing using pressure-assisted SHS or CS. The obvious challenge in all brazing (but far less with exothermic brazing) is achieving good wetting, which is so essential for obtaining good bonding. Provided wetting is achieved, strength is quite good, sealing is excellent, and temperature stability can be good for properly chosen fillers (e.g., refractory metals or ceramics) or processes (e.g., diffusion brazing). Chemical resistance varies for metal fillers but is generally excellent for ceramic fillers. Actual soldering is rarely performed, except in electronics or microelectronics, in which case metallized layers are applied to the ceramics and soldering is done between metallized layers.

Welding, including the very specialized process of "sinter bonding," offers the ultimate in temperature capability, strength, and environmental stability. Solid-phase processes, because of their applicability at low temperatures and their nondisruptive nature, offer the greatest strength potential (e.g., up to 420 MPa or 60,000 psi) in fine, structural alumina.

With every joining process, great care must be given to matching the low coefficient of thermal expansion of most ceramics with the higher CTE of other materials (e.g., most metals). The CTEs of dissimilar ceramics must also be closely matched to avoid failure by fracture, or special techniques must be employed to accommodate mismatched strains.

12.8 JOINING GLASSES

12.8.1 The Challenges Posed by Joining of Glasses

Glasses are amorphous solids that exhibit no distinct melting point or associated discontinuous volumetric change at some particular temperature. Rather, they exhibit a continuous decrease in specific volume and increase in viscosity with decreasing temperature. The rate of decrease of specific volume with decreasing temperature decreases at some point, known as the "glass transition temperature," T_g. Below the T_g, a glass behaves like a brittle solid; above it, it behaves like a decreasingly viscous liquid with increasing temperature. Bonding within glasses is primarily covalent, although some ionic and mixed primary bonding and even some secondary bonding also occur. While strength can be quite high, easily exceeding 700 MPa (100 ksi), it is far higher in compression than in tension. Unfortunately, ductility is quite low. This inherent brittle behavior is related to omnipresent microflaws (usually microcracks) introduced during processing, just as they are in crystalline ceramics.

The properties of glasses are as unique as their structure. The lack of periodicity of atoms (i.e., location on precise lattice sites) drastically reduces scattering of electrons and photons, so optical properties are unique, usually resulting in transparency or translucency in the visible or near-visible spectrum. Electrical properties can also be

unique, although glasses are usually dielectric or insulating. Glasses generally exhibit good chemical and environmental stability and are usually thermally insulating.

Like ceramics described earlier, glasses can be joined by several methods, including, in approximate decreasing order of popularity or frequency (1) welding or "fusing," (2) cementing using glassy frits, (3) adhesive bonding using organic adhesives, (4) soldering to dissimilar materials, and (5) mechanical fastening or integral attachment. The amorphous structure of glasses particularly favors welding or fusing, while their property of increasing workability (i.e., decreasing viscosity) with increasing temperature enables some special mechanical interlocking methods, especially useful for joining to metals. In fact, glasses are only rarely mechanically joined to other glasses and are much more commonly mechanically joined or sealed to dissimilar materials. For this reason, the mechanical joining of glasses will be discussed only in Chapter 15, although methods shown in Figures 12.2 and 12.5 for ceramics generally apply.

12.8.2 Welding or Fusing Glasses

Glasses are readily fused or welded to other glasses. In fact, glassworkers and glassblowers practice such fusing or welding all the time. Such welding is accomplished by heating the two pieces of glass to be joined into a temperature range where they deform or flow easily, known as the "working range."[14] Once at the proper temperature, the glasses are placed in contact, pressed together, and held under pressure to allow flow across the interface. The mechanism is bulk viscous flow rather than simple diffusion, although interdiffusion certainly occurs at the same time. The driving force is the reduction of surface area. The resulting joint is usually indistinguishable from the original, monolithic joint elements, and joint properties, including strength and physical properties, are excellent. Heating sources for welding glasses are usually oxy-fuel gas flames but can be furnaces heated by combustion or electrical sources, principally relying on convection and radiant heating, respectively. Carbon dioxide lasers have also been used successfully for fusing bonding glass.

In order to successfully weld two glasses, they must be compatible chemically, which is usually not a problem, and also in terms of coefficient of thermal expansion, which can be a problem. When there is a CTE mismatch, so-called "matched" joints are made using several other glasses with graded (or stepped) coefficients of thermal expansion as intermediates.

12.8.3 Cementing and Adhesive Bonding of Glasses

Glasses can be bonded adhesively with either inorganic or organic adhesives. When inorganic adhesives are used, the process is typically called "cementing." When the

[14] The *working range* is just one of several designated ranges of temperatures useful in characterizing the behavior of glasses. These ranges, which also include "annealing," "softening," and "melting" ranges, characterize the viscosity range of the glass at some temperature to allow certain actions to take place, like shaping, stress relieving, and pouring, respectively.

adhesive is organic, the process is simply called adhesive bonding. In both types of bonding, bonding forces are a combination of chemical (from secondary van der Waal's forces) and mechanical (from interlocking). Because glasses are generally nonporous, mechanical roughening is usually required to improve adhesion. This can be accomplished using abrasive particles (e.g., fine alumina or carborundum in a water slurry) in a grit blast, or using acid etching with a mixture of sodium dichromate and concentrated sulfuric acid in water. Glasses intended for optical use should not be acid etched, and abrasive treatment must be limited.

Inorganic cements used to join glass to glass include (1) soluble silicates of potassium or sodium (such as sodium silicate, or "water glass"); (2) basic salts of heavy metals (known as "Sorel cements"), including magnesium oxychloride; and (3) lethargic cements, which are mixtures of glycerine and lead oxide (PbO). Glass frits can also be used as cements, but because firing is required to cause bonding, these are more akin to fillers for welding or brazing if melting (i.e., softening) of the substrate is limited.

Organic adhesives for use in glass-to-glass bonding include a variety of transparent, heat-setting resins, usually exhibiting water resistance to provide environmental stability for outdoor service. Example adhesives include polyvinyl butyral, phenolic butyral, nitrile–phenolic, neoprene, polysulfide, silicone, vinyl acetate, and clear epoxies.

12.8.4 Soldering of Glasses and Solder Glasses

Glasses can be soldered to other glasses as well as to other materials, including, most importantly, metals. What is especially interesting is that the fillers used can be either metallic or special composition glasses. When they are metals (or, more properly, metallic alloys, they are called "solders." When they are glasses, they are called "solder glasses."

Metallic solder alloys for use with glass are based in indium, since these alloys, almost uniquely, are able to wet glasses. The most common alloy used is 50 wt.% In/50 wt.% Sn, with a melting range of 117–125°C (243–257°F). Joint strengths are quite good, thermal match is good, and excellent hermetic seals can be achieved. Indium solders also have extremely low vapor pressures, so they perform well in vacuum applications where glasses are frequently used.

Particular glasses have been developed specifically for soldering purposes between glasses or between glasses and other inorganic materials (such as ceramics or mica) or metallic alloys. The name "solder glass" has been given to this group of glasses on the basis of their technological similarity to metallic solders (i.e., low melting or softening temperature, wetting of glass surfaces, and adhesion to glass base materials).

In conventional glass working, two glass articles or parts are fused together (i.e., welded) and reformed at relatively high working temperatures. In contrast, solder glasses are used to join glass parts together at temperatures low enough to avoid any significant distortion due to flow or damage due to thermal shock. Excellent strength and sealing are obtained. Because of the low sealing temperatures they allow, solder glasses are widely used in hermetically sealing electronic devices.

The most difficult part of the development or formulation of a solder glass is to adjust its properties to a particular application. Usually its thermal expansion

characteristics should match those of the parts to be sealed, its viscosity should remain low within the soldering temperature range, and its chemical durability should not be lowered beyond acceptable limits. Generally, however, the lower the viscosity of a glass, the higher its thermal expansion rate and the poorer its chemical durability.

To fulfill specific requirements with respect to the foregoing properties, a wide variety of solder glass compositions have been explored and developed. Table 12.8 lists some of the more important solder glasses and their properties. Types include $PbF_2-B_2O_3-ZnO$ systems, Sb_2O_3 and As_2O_3 types, phosphate (P_2O_5)-based types,

Table 12.8 Some of the More Important Solder Glasses and Their Properties

Composition (mole %) or (wt.%)													
Sb_2O_3	As_2O_3	B_2O_3	SiO_2	ZnO	PbO	PbF_2	P_2O_5	K_2O	Na_2O	Li_2O		*CTE* ($\times 10^{-7}/^\circ C$)	*Softening Temp.* ($^\circ C$)
Solder Glasses in the $PbF_2-B_2O_3$–ZnO System													
·	·	35	·	35	·	30	·	·	·	·	·	75	440
·	·	27.5	·	32.5	·	40	·	·	·	·	·	70	470
·	·	40	·	37.5	·	32.5	·	·	·	·	·	63	490
·	·	42.5	·	32.5	·	25	·	·	·	·	·	66	490
·	·	42.5	·	40	·	17.5	·	·	·	·	·	58	510
Solder Glasses Containing Large Amounts of Sb_2O_3 and As_2O_3													
90.3	–	–	–	–	–	·	·	9.7	–	–	·	185	260
86	–	–	–	–	–	·	·	14.0	–	–	·	194	280
41	27.3	–	–	–	31.7	·	·	–	–	–	·	128	287
43.8	44.8	–	–	–	–	·	·	11.4	–	–	·	212	252
73.4	–	–	–	–	18.7	·	·	7.9	–	–	·	192	250
80.6	–	4.8	–	2.8	7.7	·	·	2.2	1.2	0.7	·	150	290
65.0	–	5.0	3.0	–	20.0	·	·	5.0	1.0	1.0	·	133	312
87.3	–	–	3.0	–	–	·	·	9.7	–	–	·	182	292
45.1	30.6	5.4	–	3.1	8.0	·	·	7.3	–	–	·	184	255
68	–	15.0	–	–	17.0	·	·	–	–	–	·	122	342
Phosphate-Based Sealing Glasses													
·	·	·	·	–	30	·	70	·	·	·	·	131	300
·	·	·	·	–	41.2	·	58.8	·	·	·	·	153	255
·	·	·	·	–	50	·	50	·	·	·	·	171	310
·	·	·	·	50	–	·	50	·	·	·	·	84.5	380
·	·	·	·	20	40	·	40	·	·	·	·	132	345
·	·	·	·	20	30	·	50	·	·	·	·	121	325
·	·	·	·	30	20	·	50	·	·	·	·	116	330
·	·	·	·	40	20	·	40	·	·	·	·	119	367

Data from Takeshi Takamori, "Solder Glasses," *Treatise on Materials Science and Technology,* Vol. 17, Minuro Tomozawa and Robert H. Doremus, (eds.), New York: Academic Press, 1985, pages 186–88.
Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 454, Table 12.6, 1993, with permission of Elsevier Science, Burlington, MA.

and CaO- and Cu_2O-containing types. Some solder glasses must be used at temperatures that exceed the normal limit of metallic solders (i.e., 450°C or 840°F) but are considered solders nevertheless.

SUMMARY

Ceramics and glasses are fundamentally different from metals, alloys, and polymers, and they even differ from one another, so joining of these materials presents some special challenges. Ceramics are crystalline, inorganic nonmetallic solids, while glasses are non-crystalline or amorphous, inorganic nonmetallic solids (except for glass polymers and metallic glasses). Both ceramics and glasses are characterized by strength that is quite high in compression and, usually, much lower in tension because of the existence of processing-induced microflaws. In ceramics, ductility is generally quite limited even to the highest temperatures at which the material remains solid. Both ceramics and glasses are extremely brittle at normal (i.e., near room) temperatures. Chemical and other environmental durability of both materials is excellent, and electrical, magnetic, thermal, and optical properties can be unique among all material types. Thus, joining to produce larger, more complex shapes can be readily accomplished by normal processing and fabrication routes. Producing hybrid structures with optimum properties is achieved through the mixing of materials and becomes critical for economic and technical reasons.

During their initial production, ceramics can be direct bonded by sintering (with or without some liquid phase or bonding aid being present) with great ease and success. The process is called ''sinter bonding'' and is almost exclusive to ceramics. Once ceramic articles have been produced, joining becomes more difficult but can be accomplished by, in decreasing order of use (1) direct joining by solid-phase nonfusion or fusion welding; (2) indirect joining by either organic adhesives or inorganic cements or mortars; (3) brazing with either metallic or ceramic fillers, or by soldering; or (4) mechanical joining with integral attachment features or fasteners.

Direct joining by welding, either in the solid state (almost exclusively by diffusion welding, with or without an intermediate, but also by friction) or by fusion (e.g., using high-energy-density laser beam or electron beam or non-transferred plasma arc welding) offers the optimum in temperature capability, strength, and environmental durability. During fusion welding, sublimation (rapid thermal decomposition of or evaporation from the melt) or thermal degradation (shock) in the heat-affected zone must all be considered, avoided, overcome, or circumvented. Indirect joining with inorganic or organic adhesives is simple, versatile, and relatively low in cost. Strength is good, but temperature capability (except for the refractory inorganic cements, unfired or fired) can be extremely limited. Sealing for hermeticity can be difficult unless the inorganic adhesive is fired or a special organic adhesive is employed. Brazing with noble metal or active metal fillers, or to refractory metal metallized layers using conventional metal braze fillers, works well and provides good strength and temperature capability. With all indirect joining methods using thin layer intermediate materials, thermal mismatch (i.e., differential CTEs) must be dealt with. This is usually

accomplished through the use of intermediates that gradually step-change the critical properties from one side of the joint to the other.

Mechanical joining by integral feature interlocking or through the use of fasteners works well, provided bearing forces and/or clamping forces do not cause intolerable stress concentrations that lead to brittle fracture. Flexibility in mechanically fastened joints must usually be provided to accommodate severely differential CTEs.

Glasses can be joined directly by welding or "fusing"; indirectly using organic adhesives or inorganic cements or using metal solders or solder glasses; or, to a far lesser extent, mechanically using either interlocking techniques or fasteners. Solders for glasses are either In-based metallic alloys or special, low-melting, low-viscosity glasses called "solder glasses."

QUESTIONS AND PROBLEMS

1. Define what is meant by a "ceramic." If this definition is correct and complete, how does it explain each of the following generic properties of ceramics?
   a. Densities greater than those of polymers but less than those of metals
   b. Exceptional tolerance of elevated temperature
   c. Exceptional resistance to chemical attack
   d. Stiffness that tends to be higher than that of most metals
2. What are some of the engineering properties of ceramics that set them aside from metals and better suit them for certain applications? What sorts of applications?
3. How is a glass like a ceramic, and how is it different? Is it possible to convert a ceramic into a glass? If so, give an example. Is it possible to convert a glass into a ceramic? If so, give an example.
4. What are some of the properties that give glasses a unique niche among materials? Why do glasses display these properties, and why do ceramics not?
5. Why is joining of ceramics and glasses so particularly important, even more than most other materials? What makes joining ceramics particularly challenging? What about glasses? Are they equally, less, or more challenging to join, and why?
6. What is meant by "sinter bonding" as it pertains to the joining of ceramics? Does it apply to glasses as well? If so, why? If not, why not?
7. Explain what is meant by "direct joining" of ceramics and glasses. Give some examples of direct bonding processes for each, i.e., for ceramics only, for glasses only, and for both.
8. Explain what is meant by "indirect joining" of ceramics and glasses. Give some examples of indirect bonding processes. Are there any differences between indirect bonding approaches for glasses compared to ceramics? If so, what differences? If not, why not?
9. What are the advantages and disadvantages of mechanically joining ceramics or glasses? What are some of the methods used? Give a familiar example of each general method. What special precautions must be taken in mechanically joining these materials?

10. Differentiate between "adhesive bonding," in its usual sense, and "cementing," in its usual sense, as these pertain to ceramics and glasses. What are the advantages of each method? What are the shortcomings of each?
11. In what generic ways are structures made from cement or concrete joined? Give a familiar example of at least three different ways. Is there anything different about joining cement or concrete from joining a typical engineering ceramic? If so, what and why? If not, why not?
12. What are the two general methods for brazing ceramics? What are the relative advantages and disadvantages of each method?
13. Describe noble-metal, active-metal, and refractory-metal brazing. Give a familiar, or reasonable, application example of each method.
14. Describe how ceramic brazing is accomplished with ceramics, and give a familiar, or reasonable, application example.
15. How is thermal spraying considered a process for joining ceramics? Explain. Give some examples of situations in which thermal spraying might be used to advantage.
16. Describe how glasses are welded. Why is it so simple to weld glasses and often so difficult to weld ceramics? What types of problems arise with ceramics that do not arise with glasses, and why? (This last part of this question is tough!)
17. Describe how glasses can be soldered. What types of solder are used? Differentiate between "glass soldering" and "solder glasses." Where are "solder glasses" used, i.e., for what purpose?
18. Can glasses and ceramics be solid-phase welded? If so, by what processes and for what reasons does this work? If not, why not?

Bonus Problems:

A. Regarding Problem #1, how are the electrical and thermal conductivity of most ceramics related, i.e., by what law (if any) and due to what inherent atomic-level structural characteristic? There is one very well known, and notable, exception to this general relationship. In what general ceramic material does this occur, and why is it so? Of what useful consequence is this notable exception in modern electronics?
B. Why do you think glass is not joined by brazing, but is joined by soldering (or is this untrue)? If it is, untrue, given an example of what might be brazing.
C. Why is masonry cement or concrete never welded? Why is it never soldered?

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Chapter 13

Joining of Polymers

13.1 INTRODUCTION

13.1.1 Polymers Defined and Classified

Polymers, commonly referred to as "plastics," are materials that are composed of long-chain molecules that can occasionally be arranged in regular arrays to render the material totally crystalline, or frequently into regions ("packets") of regular arrays connected to one another and surrounded by random arrangements of the same molecules to render the material partially crystalline (semi-crystalline). Sometimes the long-chain molecules are arranged totally randomly to produce a completely non-crystalline (amorphous) structure. The degree to which these long-chain molecules can take up regular, crystalline arrangements depends on the chain length, chain structural complexity or configuration, and processing used to produce desired product forms (e.g., sheets, films, fibers, etc.) and final parts. The larger and more complex or bulky the molecule, the less crystalline the polymer will tend to be. Processing that forces the polymer to take the shape of the final product using directed flow tends to promote crystallinity, while processing that forces the polymer to take a shape without much directed flow (and to do so rapidly under fast cooling) tends to promote non-crystallinity. The degree of crystallinity in the molecular-level structure affects the macroscopic or bulk properties of a polymer with a given chemical formula.

Within the molecular chains comprising polymers, bonding is covalent and characteristically strong. Between chains, bonding can vary from weak secondary (e.g., van der Waal's) bonding to strong covalent or even ionic bonding. When covalent or ionic bonding occurs between chains, the polymer is said to be "cross-linked," and the resulting bulk structure is more rigid and less flexible. When the bonding between chains is strictly secondary, the bulk polymer is typically weaker and more flexible ("plastic"), the quality from which its common name derives.

The molecular chains of polymers are usually based on carbon (i.e., polymeric hydrocarbons) but can also be based on silicon (i.e., silicones). The basic building block of the central chain molecule of a polymer is called a "mer." A *mer* has the basic chemical formula and structure that is repeated in the chain, creating the *poly-mer* from the many connected or bonded mers. While in this treatment only carbon-based

polymers will be considered, in all cases, the chain molecules are extremely long, typically consisting of hundreds, thousands, or even tens of thousands of mers.

As a result of their being built up of many repeating mer units, polymers typically have very high molecular weights. For a given polymer (or string of mers), the length of the molecular chain can—and does—vary statistically around some mean, and the average or mean chain length or degree of polymerization, reflected in molecular weight, can be adjusted by the polymer chemist, using certain catalysts to cause the polymerization to continue or others to cause it to cease. Thermodynamics, specifically the desire to maximize entropy, tends to cause these very long and frequently complex (and, therefore, bulky) chains to coil, twist, or kink, as well as intertwine or entangle (i.e., to tend toward disorder). The results of this are that (1) the chains have unusually high elasticity, which is the ability to stretch (to their lower entropy state) under tensile loading and then recover (to their higher entropy twisted state) upon unloading; (2) the chains exhibit viscoelasticity or viscoelastic strain behavior, which is the characteristic of continuing to elongate or strain for some time after the application (or subsequent release) of an instantaneous applied load or stress; and (3) stress relaxation, which is the ability to reduce the stress produced by a particular level of imposed strain by having molecules adjust by unkinking, uncoiling, or sliding along one another. This combined behavior is what gives polymers their unique properties (e.g., extraordinary elasticity, resilience, and formability). These properties in the bulk polymer arise from the behavior of the individual chain molecules and the interactions between these chain molecules.

Since there are many basic building blocks (i.e., mers) from which polymer molecules may be produced, and these can be arranged in many different ways within and along the central chain, there are a phenomenal number of possible polymeric materials. Chains can be of various average lengths (i.e., molecular weights), which changes the bulk polymer's behavior (e.g., softening temperature in the form of glass transition temperature,[1] tendency to crystallize, etc.). Furthermore, depending on whether chains can align easily and pack efficiently to produce crystalline or semicrystalline structures, or whether the structure of the chain is so complex and bulky that such alignment and packing are impossible (in which case an amorphous structure results), properties can also differ even for the same basic composition.

Chain molecules can consist entirely of one type of mer, different mers arranged in groups along the central spine or backbone of the molecule in clusters or groups (''block co-polymers'') or randomly (''random co-polymers''), or along secondary branches (''branched'' or ''grafted polymers''). Furthermore, various organic radicals or side groups (e.g., methyl groups, benezene rings, amines, etc.) can link to the central spine in the following ways to produce different properties (i.e., ''stereoisomerism''): randomly on both sides of the chain (''atactic''); regularly along one side of the chain (''syndiotac-

[1] Remember, only pure crystalline materials exhibit a discrete temperature at which the material reversibly changes from solid to liquid, while impure crystalline materials exhibit a melting range (between solidus and liquidus temperatures). Non-crystalline materials do not exhibit a melting point, denoted by a discontinuous change in the rate of change of the specific volume of the material as a function of temperature, but, rather, a gradual change in this rate of change of specific volume at what is called the ''glass transition temperature.''

tic"); or regularly and symmetrically on both sides of the chain ("iostactic"). There can also be alternative structures of the same basic mers known as "geometric isomers" (e.g., *cis-*, *trans-*, and *gauche-*). Finally, there is an analogue to alloying (i.e., substitution of one element in a mer for another, such as one chlorine ion for one hydrogen ion, producing a vinyl chloride mer from an ethylene mer), and many other variations. Figure 13.1 schematically illustrates some of the ways that basic polymer structures can vary.

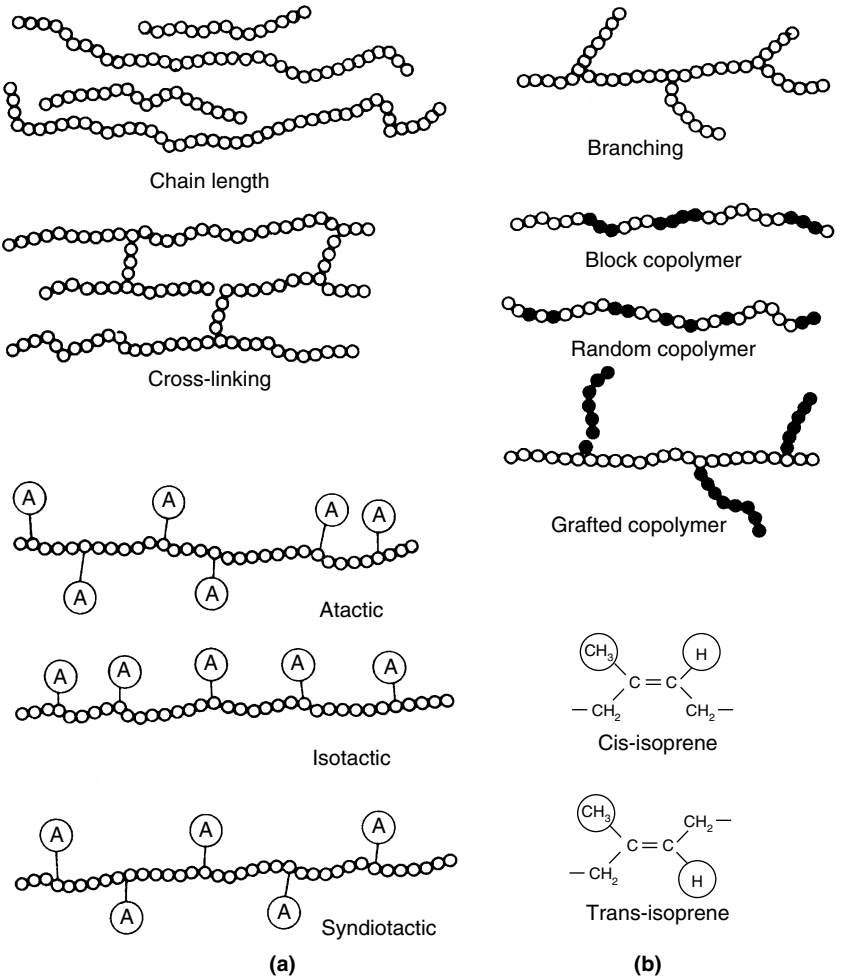

Figure 13.1 Schematic illustrations of some of the many ways polymers are created/structured, including with different chair lengths (or molecular weights) via degree of polymerization; chain branching; chain cross-linking (especially in thermosets); block and grafted copolymers; atactic, isotactic, and syndiotactic stereoisomerism; and cis- or trans-geometric isomerism. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, Fig. 13.1, page 459, 1993, with permission of Elsevier Science, Burlington, MA.)

Fundamentally, there are two types of polymers: (1) *thermosetting polymers* and (2) *thermoplastic polymers*. Briefly, thermosetting polymers tend to be cross-linked (i.e., they have primary bonds between chains). Furthermore, they cross-link or "cure" from a melt or liquid-like phase during synthesis to become irreversibly rigid (i.e., solid-like). Of the two types of polymers, the thermosets tend to be higher in strength, less elastic, more thermally durable, more chemical-resistant, and non-recyclable. Thermoplastic polymers, on the other hand, tend to have simpler molecules, exhibit far less cross-linking (if any), can reversibly soften on heating and stiffen on cooling, exhibit greater elasticity, have more limited thermal durability and resistance to chemicals (e.g., solvents), and are recyclable. Within these primary groups, there is a secondary classification known as "elastomers" or "elastomerics," which exhibit unusually high recoverable elongation upon unloading (following loading). For all types of polymers, elastomeric or not, there are dense (i.e., non-porous) forms as well as foams. Foams contain open or closed cells or pores that are produced during polymer processing to lower structural weight and improve thermal insulating qualities, energy absorption (through crushing), and vibration damping and noise abatement. Foams can be soft, pliable and non-structural, or rigid and structural.

Table 13.1 lists some of the more important and common polymeric materials of various types—thermosetting, thermoplastics, elastomerics, and rigid foams.

Table 13.1 Some Important Polymers (by Class)

Thermosetting Polymers
Diallyl phthalate (DAP)
Epoxies
Melamine–formaldehyde (melamines)
Phenol–formaldehyde (phenolics)
Thermosetting polyester
Polyimide
Polyurethane
Silicone resins
Urea–formaldehyde
Thermoplastic Polymers
Acetal copolymer (Celcon)
Acetal homopolymer (Delrin)
Acrylonitrile–Butadiene–Styrene (ABS)
Cellulous acetate, acetate butyrate, nitrate
Fluoroplastics
Nylons (polyamides)
Phenylene–oxide based resins (Noryl)
Polycarbonate
Thermoplastic polyester
Polyetheretherketone (PEEK)
Polyethersulfone
Polyethylene
Polymethylmethacrylate (PMMA)

Table 13.1 (*Continued*)

Polyphenylene sulfide (PPS)	
Polypropylene	
Polystyrene	
Polysulfone	
Polyvinyl chloride	
Elastomeric Polymers	
Natural rubber	
Neoprene (polychloroprene)	
Silicone rubber (polydimethylsiloxane)	
Butyl rubber	
Nitrile rubber (butadiene–acrylonitrile)	
Polyurethane elastomers	
Synthetic natural rubber (polyisoprene)	
Styrene–butadiene rubber (Buna S)	
Polybutadiene (butadiene rubber)	
Polysulfide rubber	
EPDM (ethylene-propylene-diene terpolymer)	
Rigid, Structural Foams	
Phenylene oxide–based resins (Noryl)	
Polyethylene	T/Ps
Polystyrene	
Polyvinyl chloride	
Polycarbonates	
Epoxy	T/Ss
Phenolics	
Polyurethanes	
Silicones	
Urea–formaldehydes	

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 460, Table 13.1, 1993), with permission of Elsevier Science, Burlington, MA.

13.1.2 The Challenge of Joining Polymeric Materials

The requirement to produce larger, more complex, and higher performance parts from polymers or plastics has created an increased need for joining these increasingly diverse and important materials. The need for a greater variety of joining methods and improved joint properties and efficiencies is also increasing because polymers, perhaps more than any other material, are being engineered to improve their strength and other functionally specific properties and, thereby, permit applications with heretofore unimagined performance expectations.

The inherent properties of polymers as well as the sheer diversity of types within polymers make the selection of an appropriate joining process more challenging than for most other materials. The extremes associated with this class of materials are more diverse than for other classes of materials. For example, all metals are fundamentally the same: they are all metallically bonded on an atomic scale; they are all crystalline in

structure and nature; they all soften and then melt upon heating; and virtually all exhibit strength with ductility and toughness (albeit quite differently between low-strength, highly ductile Pb and high-strength, highly brittle Cr). But the major engineering metals and alloys are rather uniformly strong and tough and reasonably tolerant of temperature, and their atomic-level structures are simple. Hence, the joining of metals is relatively simple, and achievable with a wide variety of approaches—mechanical fastening, integral mechanical attachment, adhesive bonding, welding, brazing, or soldering. Likewise, ceramics are all ionically and/or covalently bonded; all are crystalline in structure and nature; and virtually all exhibit high strength and high hardness with low ductility and toughness compared to metals. As a group, their atomic-level structures are more complicated than metals and alloys. Their joining is thus more complicated, especially by the most familiar processes of mechanical fastening and welding. Glasses, which are the close cousins of ceramics, are also ionically and/or covalently bonded, but they are amorphous as opposed to crystalline. Hence, they are actually less different from one glass to another, and are generally simpler to join, especially by welding or fusion bonding. Polymers, on the other hand, are always complex in structure and exhibit far greater variety and diversity, and so joining them can be more complex.

13.2 GENERAL METHODS FOR JOINING POLYMERS

The fundamental processes of mechanical fastening or integral mechanical attachment, adhesive bonding (including the special method of solvent cementing), and welding or "thermal bonding" can all be used to join polymeric materials (plastics). Brazing, soldering, and weld-brazing are not (or, at least, have not been) used. Thermal spraying is used to enable adhesive bonding in some situations by applying thermoplastic adhesives to polymeric substrates or other substrates. Weld-bonding is theoretically possible, at least for thermoplastics, but seemingly has not been used commercially and may offer few if any distinct advantages.

To date, if polymeric materials have been used to make semi-structural and structural parts (i.e., secondary and primary structures, respectively), they have most likely been thermosetting polymers, with or without reinforcement (e.g., in epoxy–graphite aircraft parts and epoxy–glass recreational boat parts, including hulls). Mechanical fastening and adhesives have been used to join these polymers. However, thermoplastic's greater impact resistance, easier processing (including assembly, but especially molding), and potential for recycling[2] are increasing interest in making parts

[2] There are at least two levels of recycling that are important for all materials, and particularly for plastics. In primary recycling, materials are recovered, reclaimed, and reused (i.e., are recycled) within the manufacturing environment, as part of the overall manufacturing process. This prevents waste by maximizing material utilization and minimizing waste or scrap. In "secondary" recycling, materials are recovered, reclaimed, or reused (i.e., recycled) from products that have lived out their useful lives. In fact, within this category for plastics there are two sub-levels: one called secondary, which recovers waste plastics specie by specie, and the other called ternary, which recovers plastics as a group or commingled.

Table 13.2 Summary of General Methods for Joining Polymers

Mechanical Joining Methods
- Mechanical fastening:
  - self-tapping screws with either large heads or washers
  - nuts and bolts (or screws) with either large heads or washers, and, perhaps, sleeved holes
  - large head upsetting rivets or pop-rivets
  - upsetting thermoplastic rivets
  - snap-fit fasteners
  - eyelets and grommets
- Integral mechanical attachments (designed-in or formed-in)
  - molded snap-fit (design features)
  - thermal staking (formed-in features)

Adhesive Bonding Methods
- Thermoplastic adhesive bonding of thermoplastics
- Solvent cementing of thermoplastics
- Thermosetting adhesive bonding of thermosets
- Co-cured thermosetting polymer assemblies
- Adhesive alloy bonding of mixed thermoplastics and thermosets

Welding or Thermal Bonding Methods (for Thermoplastics)
- Welding or thermal bonding using external heat sources
  - hot plate welding
  - hot gas welding
  - infrared welding
  - RF welding
  - induction welding (using an embedded conductive mesh)
  - resistance welding (using conductive metal coatings)
- Welding or thermal bonding using internal heat sources
  - friction welding (using spin, linear vibration, or angular reciprocation)
  - ultrasonic welding
  - friction stir welding

from that polymer type. While adhesives and mechanical fasteners have also been used for joining thermoplastics, these polymers, because of their inherent characteristic of reversibly softening upon heating and hardening upon cooling, offer an alternative joining possibility that is still in its relative infancy, namely, welding or "thermal bonding." Both types of polymers offer the possibility of mechanical attachment using molded-in integral attachment features known as "snap-fits," although this approach is more popular in thermoplastics because of their easier molding.

Table 13.2 summarizes the general methods for joining polymers by their major types.

13.3 JOINING THERMOSETTING POLYMERS

13.3.1 Challenges Posed to Joining by Thermosetting Polymers

Thermosetting polymers (“thermosets”) are those polymers that become rigid upon curing after synthesis and remain irreversibly rigid (i.e., “set”). It is this fundamental behavior of thermosets that precludes joining by welding, at least as it is now known. Heating thermosets and applying pressure will not cause melting or even softening, so bonds cannot be created across an interface in this way. The predominant methods for joining thermosetting polymers are thus mechanical joining and adhesive bonding, with adhesive bonding being the much more common.

13.3.2 Mechanical Joining of Thermosetting Polymers

Thermosetting polymers can be mechanically joined using predominantly threaded or unthreaded fasteners as well as by employing integral interlocking design features (i.e., integral attachments). When fasteners are used they are typically made from metals, but there are good reasons why they perhaps should not be.

When using mechanical fasteners (or integral mechanically interlocking design features, for that matter), the viscoelastic deformation behavior of polymers must be considered to avoid continued deformation under constant load, and/or stress relaxation. In viscoelastic deformation behavior, as shown in Figure 13.2, an instantaneously applied load, P, causes an instantaneous strain response, ε, and a time-dependent strain response, $\varepsilon(t)$. While the specific form of the strain response differs with specific polymer types, all polymers exhibit some form of viscoelastic deformation behavior. The time-dependent deformation is often called “cold flow.” Cold flow in polymers (which really involves the thermally assisted realignment of long-chain molecules to attempt to accommodate the forced strain) can cause distortion of a fastener hole or design feature responsible for interlocking under a bearing stress and can lead to fastener loosening, fastener pull-out (especially through the thickness of thin materials), release of interlocking feature engagement, and, eventually, joint failure.

Besides this macroscopic deformation, which can cause loss of function of a fastener, an attachment feature held under a load, or a joint, part, or assembly, this time-dependent strain can also lead to the relaxation of stress within the polymer. When a polymer is forced to undergo a fixed strain, as when a rubber band is stretched over a fixed-length object, the aforementioned thermally assisted molecular realignment results in a lowering of the stress needed to maintain that fixed strain. This is known as “stress relaxation” and can result in loosening as relaxation progresses. Stress relaxation is particularly problematic for fasteners (such as bolts) that rely on clamping force or preload to achieve needed joining forces (see Chapter 2, Subsection 2.5.1). Because stress relaxation virtually always occurs in polymers, integral attachment features that rely on elastic deflection and recovery for their effectiveness must be allowed to recover to lower the stress held on them. If they are not allowed to recover, this stress will relax and the locking feature may disengage.

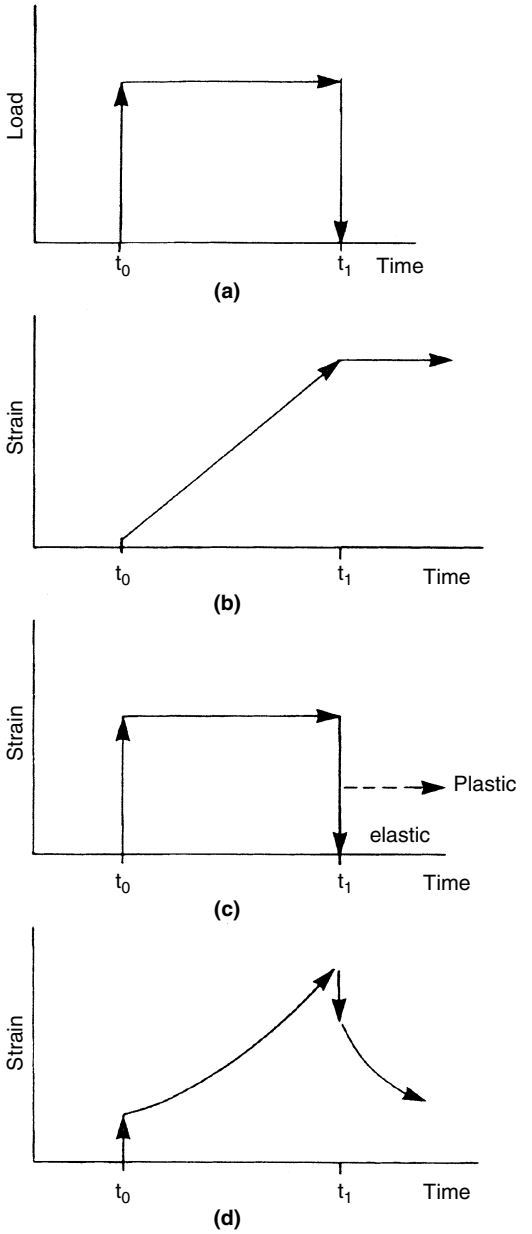

Figure 13.2 Schematic plots showing the strain behavior of various materials, including the viscoelastic behavior of polymers. A square-wave load is applied (a), with strain responses differing for materials exhibiting (b) viscous, (c) elastic or elastic–plastic, and (d) viscoelastic behavior. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, Fig. 13.2, page 463, 1993, with permission of Elsevier Science, Burlington, MA.)

Mechanical fasteners used with polymers should have large bearing areas at their heads and tails or feet and/or should be used with washers to spread loading to avoid viscoelastic deformation problems under concentrated stress. Fastener holes can also be sleeved to help reduce localized bearing deformation, often using metal grommets, for example. Loading must be limited when using mechanical fasteners or, to a lesser extent, with interlocks, since stress concentrations arise and aggravate viscoelastic deformation and tear-out. While metal fasteners are usually used to join polymers when fastening is used, the use of fasteners that are themselves made from polymers could make sense. Provided the fastener was made from a polymer with a higher stiffness (i.e., flexural modulus) than the joint material, some clamping force could still be imposed, with suitable load spreading under the fastener's head and foot. For ease of installation, thermoplastic rivets could even be used, being upset or "set" by heat. This is just like a process known as "thermal staking," in which integral posts protruding from one part are forced to pass through holes in a mating part, and the posts are then upset, thermally forming a tail just as on an upset rivet.

Because polymers are inherently corrosion resistant, there is no problem with electro-chemical mismatch between joint elements or with fasteners. Thermal mismatch is usually not a problem either, because use temperatures tend to be limited as a result of the inherent limitations of the material and the viscoelasticity of the polymer. The viscoelasticity of the polymer in the fastener or in the part allows thermally induced strains to be accommodated.

Figure 13.3 schematically illustrates the predominant failure modes for mechanically fastened and integrally attached polymers and shows some techniques for minimizing such failures.

13.3.3 Adhesive Bonding of Thermosetting Polymers

Most thermosetting polymers are relatively easy to join or bond using adhesives, so adhesive bonding tends to be the most popular joining method used with these materials. Because thermosets are not particularly soluble, solvents are of little use in causing softening to aid adhesives or for solvent cementing (to be defined later).

In general, conventional adhesive bonding using compatible adhesives is the most practical way to join a thermosetting polymer to a thermosetting polymer or to a non-polymeric material, for that matter. The best adhesives used for bonding thermosetting polymers are thermosets themselves. Some examples of adhesives used for bonding thermosetting epoxies are modified acrylics, epoxies, polyesters, phenol-formaldehydes, and cyanoacrylates. For joining phenolics or phenol formaldehyde, neoprene and urethane elastomers, epoxies and modified epoxies, cyanoacrylates, and phenolic adhesives are used. For joining polyurethanes, elastomeric adhesives, epoxies and modified epoxies, and neoprene adhesives are used, while for joining silicone resins, silicone rubber and silicone resin adhesives are used. Adhesive alloys also work well with thermosets, especially when they are being joined to other polymer types (e.g., thermoplastics). Reinforced thermosetting polymers (e.g., containing glass

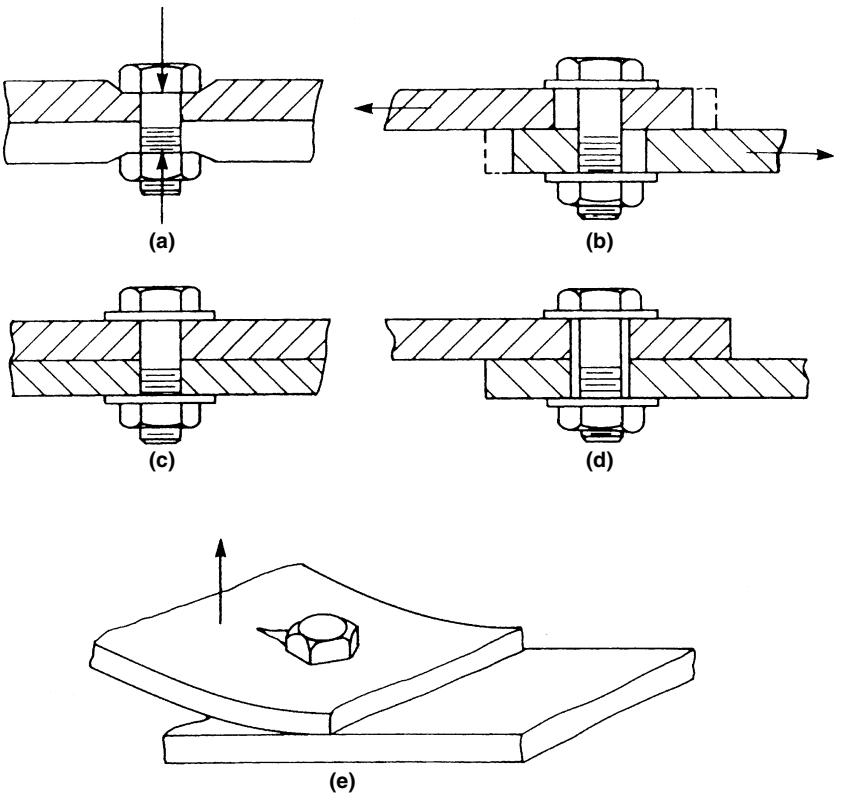

Figure 13.3 Schematic illustration showing the predominant failure modes for mechanically fastened polymers. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, Fig. 13.3, page 464, 1993, with permission of Elsevier Science, Burlington, MA.)

fibers or other synthetic high-strength fibers) are bonded by considering the base (matrix) resin (see Chapter 14) and selecting a compatible adhesive.

Adhesively bonded thermosetting polymers, whether monolithic or reinforced, can generally carry greater loads than mechanically fastened thermosets because loading is uniformly distributed over a larger area, resulting in lower stresses. Maximum stress is limited to the strength of the adhesive used, provided bonding is performed properly.

13.4 JOINING THERMOPLASTIC POLYMERS

13.4.1 Challenges Posed to Joining by Thermoplastic Polymers

Thermoplastic polymers are those polymers that can be reversibly softened and hardened by heating and cooling once they have been synthesized. As a group,

thermoplastics tend to exhibit lower strengths, lower flexural moduli, and greater elasticity, but more limited tolerance of temperature and of solvents, than thermosets. But, of course, there are specific types within each group that deviate from one or more of these generalities. The properties of thermoplastic polymers are the result of the general absence of cross-linking between the long-chain molecules, which tends to create more rigid networks in thermosetting polymers. Like thermosetting polymers, thermoplastic polymers can be joined by mechanical means, using either fasteners or employing integral, interlocking design features, and by adhesive bonding using appropriate adhesives as well as a special technique using only solvents to cause softening in "solvent cementing." Unlike their thermosetting cousins, thermoplastic polymers can be joined by welding, or what is known in the parlance of the polymer community as "thermal bonding," using either fusion or non-fusion techniques.

13.4.2 Mechanical Fastening of Thermoplastic Polymers

Thermoplastic polymers can be joined using strictly mechanical forces that rely solely on geometric interference and interlocking, whether from supplemental devices or parts (known as "fasteners") or from molded-in integral design features. In fact, the use of integral attachments, primarily in the form of elastic snap-fit features, is growing rapidly compared to the use of rigid or plastic types of features (see Chapter 3, Subsection 3.5.2). The growth of integral attachment features is a consequence of the inherent ease with which these polymers can be molded into complex shapes. While thermosetting polymers can also be molded to create rigid interlocking features and elastic snap-fits, they cannot be made to join using plastic interlocks. Whether fasteners or integral features are employed, generally lower strength thermoplastics tend to be more prone to problems from viscoelastic deformation in the form of cold flow or stress relaxation. Hence, for thermoplastic polymers, the design or choice of the fastener must be carefully considered, both for the fastener itself (e.g., to prevent pull-through in thin materials or to prevent hole elongation under concentrated bearing loads) and for any needed fastener hole (e.g., hole placement relative to edges).

As for thermosetting polymers, fastener loading should be distributed as much as possible to avoid stress concentrations that will lead to time-dependent deformation. Heads and feet of fastener systems should be as large as practical or the area around a hole should be reinforced (e.g., by making that area thicker or adding a "doubler"). Washers should be employed and/or holes ought to be sleeved. While not very common (especially for true structural applications), fasteners that are themselves made from thermoplastics might be a logical, if not ideal, approach to mechanically fastening thermoplastics. Many good arguments can be made as to why a fastener should be made of the same material as the joint elements being joined.

Typical failure modes and remedies are shown schematically in Figure 13.3.

13.4.3 Integral Snap-Fit Attachment of Thermoplastics

The basis for so-called "snap-fit" integral attachments is the use of integral attachment features that operate by elastically deflecting to allow some hook- or catch-like geometric detail to pass over and finally elastically recover and engage to cause locking with some mating catch- or hook-like detail. The "snap" in the name refers to the audible and tactile signal given off when these features are properly engaged to lock one to the other. As a group, snap-fits are what are classified as "elastic integral mechanical interlocks" in Subsection 3.5.4 of Chapter 3. The inherent elastic nature of most polymers is ideally suited to these types of attachments. The particular ease with which the occasionally intricate geometry of snap-fits can be produced in thermoplastic parts, by a variety of molding processes, makes these attachments technologically and economically attractive in parts made from these materials.

A wide variety of snap-fit types can be found in diverse products made from polymers, especially thermoplastic polymers, including automobile trim, computers and peripheral hardware, conventional and wireless telephones, children's toys, lawn and garden power tools, medicine bottles, and many, many others.

Integral snap-fit attachment features have been classified (Genc *et al.* (1998a)), and the remarkably simple, consistent use of a "catch" and a "latch" type detail in mating parts has been proposed (Messler *et al.* (1997), Genc *et al.* (1998b)). Figure 13.4 schematically illustrates various snap-fit attachments employing various possible latch and catch features.

13.4.4 Adhesive Bonding and Solvent Cementing of Thermoplastics

Thermoplastic polymers can be readily adhesive-bonded by heating and using so-called hot melts (see Chapter 5, Subsection 5.4.8) or by using certain adhesives thinned with solvents to allow easy application. Unlike thermosetting polymers, thermoplastics ordinarily require that their surfaces be physically and/or chemically modified to produce acceptable adhesion. This is especially true for crystalline thermoplastics such as the polyolefins (e.g., polyethylene and polypropylene), linear polyesters, and fluoropolymers (i.e., Teflon). Once they are modified, bonding can be accomplished with or without the aid of actual active agents or adhesives, depending on the particular polymers involved in the joint and on the application requirements.

Methods of activating the surface of thermoplastic polymers include (1) oxidation by means of chemical or flame treatment; (2) electrical (or coronal) discharge to leave a more reactive surface; (3) ionized inert gas to strengthen the surface by cross-linking and leave it more active; or (4) metal ion treatment. Adhesives for use with thermoplastics are themselves thermoplastics and include cellulose acetate, cellulose acetate butyrate, cellulose nitrate, polyvinyl acetate, polyvinyl vinylidene, polyvinyl acetals, polyvinyl alcohols, polyamides, acrylics, and phenoxies. Reinforced thermoplastics are joined by the same adhesives as those used for the matrix resin species in its monolithic form, as will be discussed in Chapter 14.

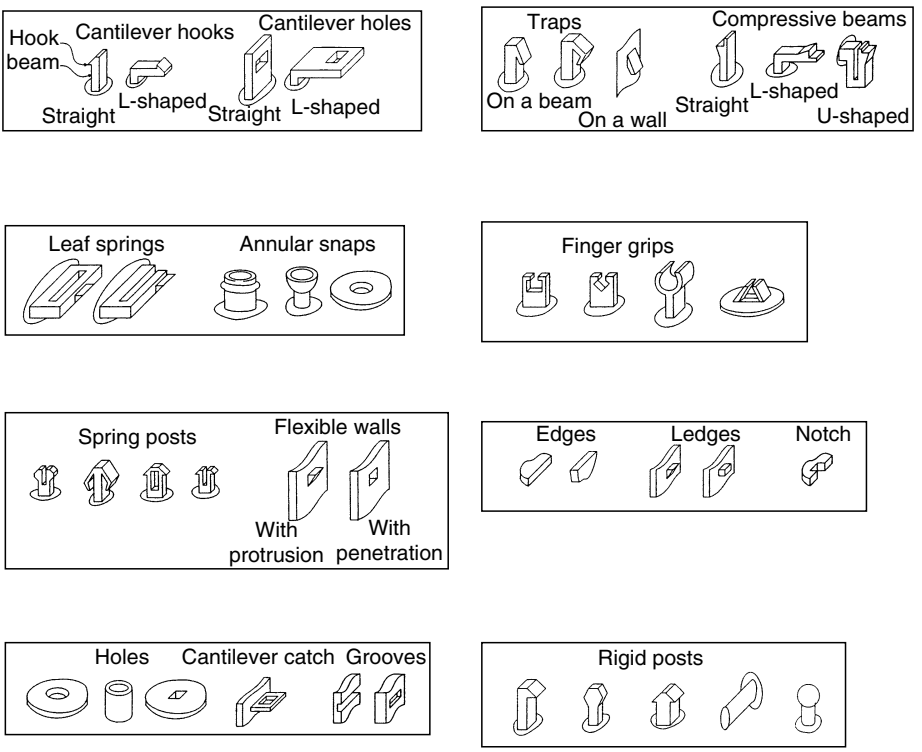

Figure 13.4 Schematic illustration of various concepts for snap-fit attachment features, all of which employ the combination of a latch and a catch. (Reprinted from ''Methodology for locking feature selection in integral snap-fit assembly,'' S. Genc, R.W. Messler, Jr., and G.A. Gabriele, *Proceedings of the 1997 ASME Design Engineering Technology Conference* (DETC'97), Sacramento, CA, September 14–17, 1997, with permission of the ASME.)

A special option available for joining thermoplastic polymers that is not appropriate for thermosetting polymers is ''solvent cementing.'' *Solvent cementing* is a process in which thermoplastics, usually amorphous, are softened (actually, are partially dissolved) by the application of a suitable solvent or mixture of solvents, and then the softened joint faces (i.e., faying surfaces) are pressed together to effect a bond. The thermoplastic resin of the joint element (i.e., adherend) dissolves into the solvent to become the active adhesive agent. After evaporation of the solvent, this dissolved polymer serves as the bonding agent. Any bonds produced by this method are principally covalent bonds, but most of the actual adhesion arises purely from the physical entangling and interlocking of the ''solvent-loosened'' long-chain molecules. Joint strength can be very high compared to normal adhesive-bonded joints in which only secondary bonding occurs. The final joint is virtually free of any remnant of the original interface for like-composition adherends. From many perspectives, solvent cementing results in joints that appear to have been welded, and, in some

sense, solvent cementing may as appropriately be seen as a welding process as an adhesive-bonding process. A well known example of solvent cementing is the application of polyvinyl chloride patches to polyvinyl chloride swimming pool liners, using acetone to soften the patch and, if it is not under the water, the pool liner.

Many thermoplastic resins, in either monolithic or reinforced composite form, are easier to join effectively by solvent cementing than by more conventional bonding with actual adhesives. Mixed solvents often give the best results, and, often, small amounts of the polymer or polymers to be cemented are dissolved in the solvent or solvents to form what is referred to as a "bodied cement." These aid in gap filling, accelerate setting, and reduce shrinkage and, thus, internal stresses.

13.4.5 Welding or Thermal Bonding of Thermoplastic Polymers

Just as in the welding of metals, thermoplastic polymers can be joined by softening or melting the base material through the application of heat and effecting bond formation by applying pressure. Fusion processes for joining thermoplastics and thermoplastic-matrix composites involve heating the polymer to a viscous state and physically causing polymer chains to interdiffuse, usually by pressure-induced flow. The resulting adhesion is largely the result of chain entangling but can include secondary and even primary covalent bonding. Consequently, joint strength is typically quite high compared to conventional adhesive bonding (although not compared to solvent cementing) and can easily approach the strength of the adherend(s).

Welding or *thermal bonding* processes for thermoplastics can be divided into two categories: (1) processes involving external heating (e.g., hot plate, infrared, hot gas, resistance, and radio frequency heating), and (2) processes involving mechanical movement to produce internal heating (e.g., frictional heating by vibration, spin, and orbital processes or by ultrasonic processes). All of these processes have several attractive attributes, including speed, strong and highly efficient joints, tolerance of contaminated surfaces, suitability for difficult-to-bond substrates, excellent bond line control, and improved recyclability.

Processes Involving External Heating

Contact with a heat source results in softened or melted[3] thermoplastic polymer surfaces in the weld area. Forcing these surfaces together results in intermixing of the molecular chains and the creation of a weld.

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[3] Recall that fully amorphous polymers, like all amorphous materials, do not exhibit a distinct melting point. Rather, they exhibit a glass transition temperature (or temperature range) above which the material behaves like a liquid and below which it behaves like a solid. The transition is continuous and is manifested as a continuous change in viscosity. For this reason, it is not accurate to refer to the softening of a thermoplastic upon heating as "melting."

In *hot plate welding,* heated metal or ceramic platens or bars clamp and heat the thermoplastic joint elements, pressing the heated mating parts together to a preset pressure for a preset length of time to create an upset and a bond (see Figure 13.5a). The process is capable of producing weld strengths equal to the parent polymer and can be used with dissimilar thermoplastics, provided they are chemically compatible (which most types are). With dissimilar thermoplastics, each platen heats each thermoplastic to its proper softening point (i.e., above its T_{glass} or T_g) and not necessarily to the same temperature. Filler material (in the form of either a similar or more pliant and lower-T_g thermoplastic) may or may not be needed and used. Obviously, heating platens or bars need to be shaped to the contour of the parts being joined, and so may be custom designed and built for a particular joining application. The process has been used for thermal bonding or welding (sometimes called "plastic welding") of plastic battery acid cases, fuel tanks, fuel filler pipes, and large pipes for water, gas, sewage, and chemical transport. The process offers excellent portability to a work site, including construction sites.

In *hot gas welding,* a stream of heated gas (e.g., nitrogen, carbon dioxide, hydrogen, and oxygen) or air is directed at the joint area to fuse the surfaces (see Figure 13.5b). A filler rod may be used, just as in metal welding. When filler is used, it should have the same composition as the joint elements or substrates, although dissimilar thermoplastics can be joined using filler that is compatible with each. Joints are usually V-grooved to provide access, or, alternatively, fillet welds can be made. Gas temperatures depend on the polymer being welded but typically fall in the range of 200–300°C (392–572°F), and gas flow rates vary from 15–60 liters/min (32–127 ft^3/hr). Gas choice depends on the need to protect the polymer from oxidation by using an inert gas (e.g., nitrogen or carbon dioxide), or to activate the surface of the polymer to cause it to bond better using either a reducing (e.g., hydrogen) or oxidizing (e.g., oxygen) gas or air. Typical thermoplastics welded using this process include polyvinylchloride (PVC), polyethylene (using non-oxidizing gas), polypropylene, polymethylmethacrylate, polycarbonates, and nylons. Hot air hair dryers or higher wattage industrial dryers are commonly used to join PVC piping.

Infrared heating is sometimes used as an alternative to hot plate heating. An infrared radiation (lamp) source, focused on the weld joint face, is used for heating. *Radio frequency welding* uses radio frequency radiation (around 27 MHz) to heat polymers that have inherent polar molecules. Unlike with induction welding, no conductor is involved or required. The process has been used for sealing PVC, nylons, and other thermoplastics with strong polar molecules. *Induction welding* is similar to radio frequency welding, except a conductive material is heated by the radio frequency radiation through I^2R eddy current effects. This heat is used to heat the thermoplastic indirectly. Tapes of thermoplastics filled with iron oxide powder work well, as do embedded wire meshes or screens. The mechanism of induction welding is shown in Figure 13.5c.

In a final method, *resistance welding,* the resistance to electrical current is used to heat a conductive element that is coated with a thermoplastic and welded (Figure 13.5d). The process has been used for making complicated joints in vehicle bumpers and panels, pipes, containers, and medical devices.

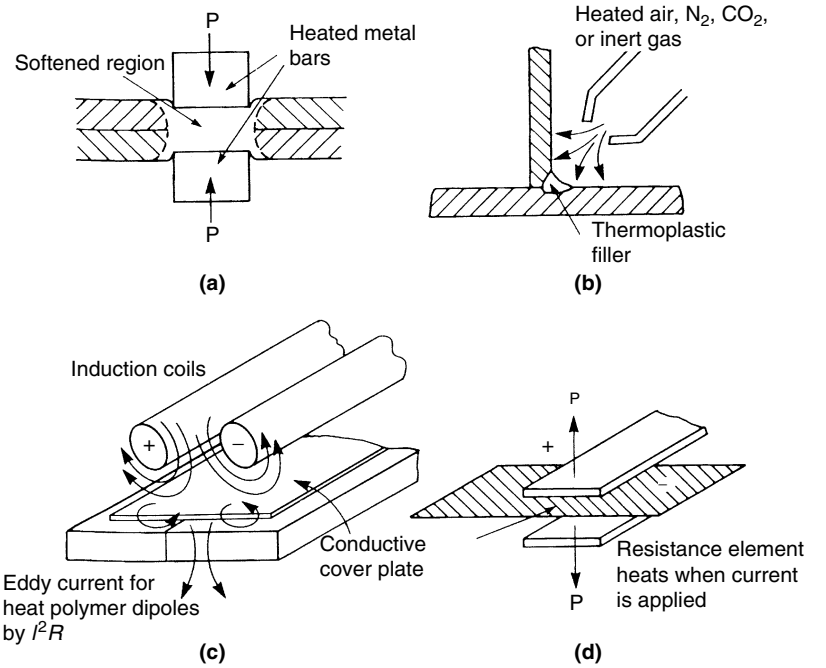

Figure 13.5 Schematic illustration of various thermoplastic welding processes using external heating sources, including: (a) hot bar welding; (b) hot gas welding; (c) induction welding; and (d) resistance welding. (Reprinted from *Joining of Advanced Materials,* Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, Fig. 13.4, page 468, 1993, with permission of Elsevier Science, Burlington, MA.)

Processes Involving Internal, Frictional Heating

In processes involving frictional heating, the heat needed to soften the thermoplastic is provided by simple friction or hysteresis heating. In *friction welding,* a spin or orbital welding process was first reported in the late 1930s and remains essentially unchanged today. It involves fixing one joint element while the other is given a controlled angular velocity, bringing the two into contact to cause frictional heating, and upsetting them to effect a bond. The process is shown in Figure 13.6a. Parameters include rotational speed (1–20 m/sec or 3.3–65.6 ft/sec), friction-producing pressure (80–150 kPa or 11.6–21.7 psi), upsetting or forging pressure (100–300 kPa or 14.5–43.5 psi), and welding time (1–20 sec). Because heating depends on relative surface velocity, it varies across a cross-section and so can lead to weld zone residual stresses. While a drill press can be used, a controlled energy source like a flywheel is better. Advantages of the *spin* or *orbital welding* process, when it is done properly, are high weld quality, simplicity, speed, and reproducibility. The principal disadvantage is that only limited, rotationally symmetric shapes can be welded.

Another form of friction welding is *vibration* or *linear friction welding*. This involves rubbing two thermoplastic components together under a suitable pressure,

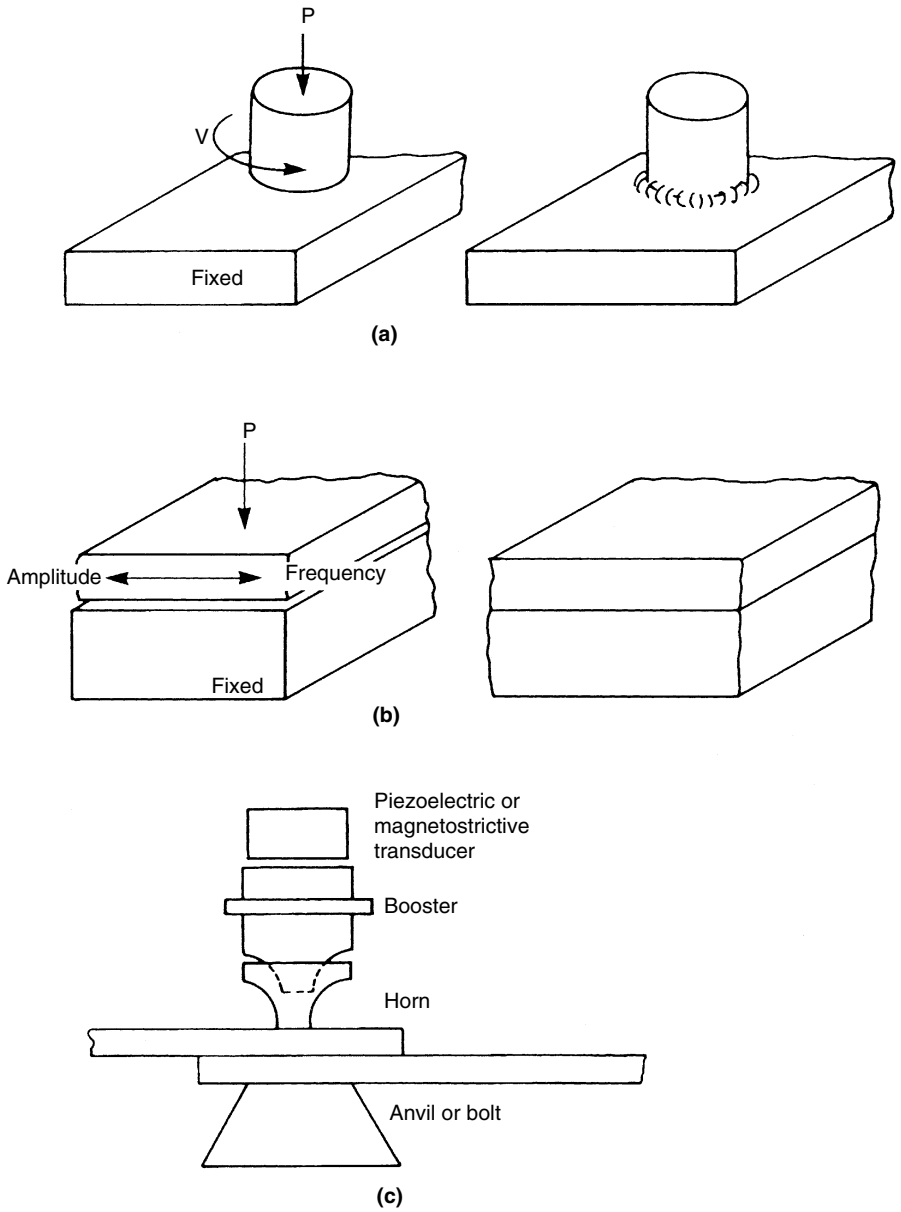

Figure 13.6 Schematic illustration of various thermoplastic welding processes using internal (friction) heating sources, including (a) friction spin or orbital welding; (b) linear friction or vibration welding; (c) ultrasonic welding; and (d) friction stir welding. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Butterworth-Heinemann, Stoneham, MA, Fig. 13.5, page 470, 1993, with permission of Elsevier Science, Burlington, MA.)

frequency, and amplitude for long enough to generate enough heat to soften the polymers. At this point, vibration is stopped and the parts are aligned and allowed to harden into a weldment. The process (shown in Figure 13.6b) is like spin or orbital welding, except that the motion is linear rather than rotational. The vibration welding process is suitable for most thermoplastics, including amorphous and semi-crystalline forms. Welds are produced in seconds using vibration amplitudes of one-half to a few millimeters and frequencies ranging from 100–500 Hz. The process is especially useful for welding crystalline thermoplastics such as acetal, polyethylene, nylons, and polypropylenes that are not easily welded by solvent cementing or other welding methods.

In *ultrasonic welding,* small-amplitude vertical oscillations at frequencies of 10–50 kHz (usually 20–40 kHz) are passed through polymers to be dissipated by a combination of friction and hysteresis.[4] Oscillatory frequencies are generated by piezoelectric or magnetostrictive crystals mounted between two blocks of metal (called "converters"). Since the amplitudes of vibration in the crystal are usually quite small, they are boosted by mass and geometric effects in a booster and horn (Figure 13.6c). At the horn, amplitudes are usually 20–60 micrometers (μm). Joints often contain projections to accentuate heating in this process.

Ultrasonic welding is currently the most common welding process used with thermoplastics. It is fast (occurring in seconds), results in little upset or flash, and is easy to automate. Applications include joining of plastic flash cubes for cameras, automobile dashboard assemblies, audiotape and videotape cassette bodies, and luggage tags.

The latest process being used for joining thermoplastics is friction stir welding. It is performed exactly as described in Chapter 6, Subsection 6.5.3, and as shown in Figure 13.6d.

Figure 13.7 shows how thermal bonding is used in the joining of modern military aircraft fabricated from thermoplastic materials.

13.5 JOINING ELASTOMERIC POLYMERS OR ELASTOMERS

An *elastomer* or *elastomeric polymer* is defined as a macromolecular material that, at room temperature, is capable of recovering substantially in size and shape after the removal of a deforming force. Elastomers are composed of very long, coiled, kinked, or tangled polymer chains. The molecules of elastomers are usually simple (although long), with few bulky side groups or radicals and little or no branching or cross-linking. Applying a load tends to straighten or align these molecules to accommodate the forced strain, causing a change in macroscopic size or shape. When the applied load is removed, the molecules attempt to return to their tangled and kinked higher entropy, lower–free energy state. Elastomers can be thermosetting or thermoplastic polymers but are more often thermoplastics.

Joining these highly pliable or flexible materials is always accomplished by adhesive bonding. To be successful, elastomeric polymers are best bonded using

[4] *Hysteresis* is the loss of strain energy that can occur on reversed mechanical loading from various sources such as internal friction. In mechanical load reversals, hysteresis causes heat generation.

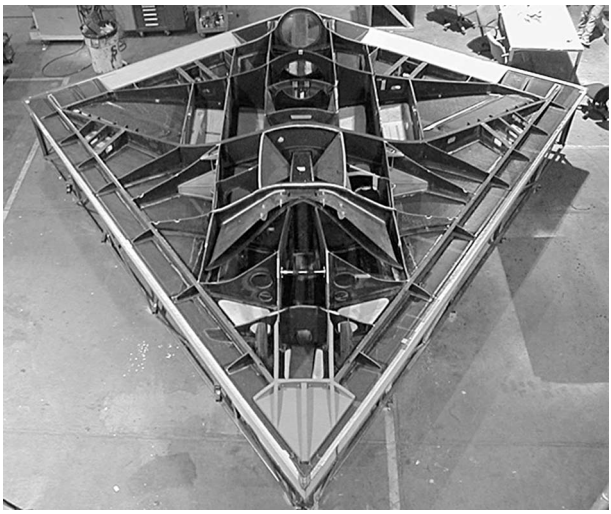

Figure 13.7 The use of thermal bonding, as well as adhesive bonding, is commonplace in the assembly of thermoplastic monolithic and reinforced composites used in military aircraft. (Courtesy of Northrop Grumman Corporation, with permission.)

pressure-sensitive adhesives derived from an elastomer similar to the one or ones being bonded. Some typical adhesives used for bonding elastomers to themselves or to other materials (e.g., polymers, wood, metal) are rubbers, neoprene, acrylics, cyanoacrylates, and epoxies. The key need in bonding elastomeric polymers is to have the joint also be pliable.

13.6 JOINING STRUCTURAL OR RIGID FOAM POLYMERS

Plastic foams can be produced from thermosetting or thermoplastic polymers by creating either open or closed cells during initial polymer synthesis, or as a secondary foaming operation in the dense, unfoamed polymer. Usually, gas-producing reactions are used, but it is also possible to simply blow gas into the liquid polymer. The resulting foams can be soft and easily compressible, or rigid. Rigid foams can be used for structural applications where light weight is critical, or where vibration damping, shock (or impact) absorption, or thermal insulation is required. Rigid foams are often called ''structural foams.''

Rigid or *structural foams* are always joined by adhesive bonding. For joining thermoplastic foams, solvent cementing is usually preferred over conventional adhesives. Care must be taken not to collapse the cells of structural foams during bonding, since these cells impart the desired properties of light weight, good thermal insulation, and impact protection. When adhesives are used, water-based types based on polyvinyl acetate and neoprene are frequently selected. For thermosetting foams, epoxies and a variety of other adhesives normally used with the dense forms of these thermosets can be successfully employed. When adhesives are used, whether they are thermoplastic or thermosetting, it is usually preferable to thin them with a solvent.

13.7 JOINING DISSIMILAR POLYMERS

Dissimilar combinations of polymers requiring joining can include thermosetting types to thermoplastic types, or thermosets or thermoplastics to elastomers or rigid foams. For all of these combinations, adhesive bonding is the preferred, and almost exclusive, method of joining.

For most of these dissimilar combinations, adhesive alloys composed of appropriate combinations of the basic materials involved in the joint are recommended. For joining thermosetting and thermoplastic types, *adhesive alloys* containing mixtures of thermosetting and thermoplastic adhesives, preferably based on the same polymers, are recommended. Likewise, for thermoplastic polymers to thermoplastic elastomers, thermoplastic/thermoplastic elastomer alloys are recommended. For thermoplastics or thermosets to be joined to elastomers of the opposite fundamental polymer type, alloys of thermosetting–thermoplastic–elastomeric adhesives are recommended.

Table 13.3 lists suggested adhesives and adhesive alloys for various combinations of thermosetting, thermoplastic, and elastomeric polymers and foams.

Table 13.3 Adhesives and Adhesive Alloys for Joining Various Combinations of Polymers

Thermosetting Polymers
For epoxies
Modified acrylics
Epoxies
Polyesters (thermosetting types)
Phenol–formaldehyde
Cyanoacrylates
For phenolics
Neoprene elastomers
Urethane elastomers
Epoxies and modified epoxies
Cyanoacrylates
Phenolics
For melamines
Epoxies
Polyurethanes
Neoprene
Cyanoacrylates
Urea–formaldehyde
For polyurethanes
Polyurethanes
Polyurethane elastomers
Epoxies and modified epoxies
Neoprene
For silicone resins
Silicone rubbers
Silicone resin adhesives

(*Continues*)

Table 13-3 (*Continued*)

Thermoplastic Polymers
Solvent cementing
For cellulosics
Natural rubber
Neoprene rubber
Nitrile rubber
Resorcinol–formaldehyde
Cyanoacrylates
For polyamides
Phenolics
Resorcinol–formaldehyde
Epoxies and modified epoxies
Polyurethanes
Cyanoacrylates
For polycarbonates
Epoxies
Urethanes
Silicones
Cyanoacrylates
Hot melts
For polyvinyl chloride
Nitrile rubber
Polyurethanes
Neoprene
Modified acrylics
Anaerobics
Elastomer Polymers
Pressure-sensitive adhesives
Neoprene
Nitrile rubber
Polyurethanes
Natural, reclaimed, butyl, nitrile, butadiene, and other rubbers
Rigid Foams
Solvent cementing
Nitrile rubber
Flexible epoxy
Rubber-based adhesives

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, pages 472, 473, Table 13.2, 1993, with permission of Elsevier Science, Burlington, MA.

For joining the dense forms of thermosetting and thermoplastic polymers to one another, mechanical fastening or integral attachment methods can be used, with the usual precautions.

SUMMARY

Polymeric materials are composed of large, complex molecules (known as macromolecules), often based on organic hydrocarbons or, in so-called "silicones," on silicon. There are innumerable varieties of polymeric materials, due to (1) the range of molecular weights (i.e., chain lengths or degree of polymerization) within a particular polymer; (2) the chain configuration (i.e., combinations and arrangements of monomers within the chain); (3) the degree of cross-linking between or networking among chains; (4) types and arrangement of side groups or radicals on chains (i.e., stereoisomerism); (5) the geometric arrangement of elements within the monomer building blocks of the polymer (i.e., geometric isomerism); and (6) degree of amorphism or crystallinity. Two primary types characterize all polymers, however: (1) thermosetting polymers or thermosets that cure upon synthesis into irreversibly rigid structures and (2) thermoplastic polymers or thermoplastics that can be reversibly softened and hardened by alternatively heating and cooling. Within each of these primary types there is a major secondary type: elastomerics that exhibit unusually high recoverable elasticity. Within the two primary types and secondary subtypes there are two general forms: dense polymers and foamed polymers, with both soft, pliable, non-structural and rigid, structural types. The foams contain either open or closed cells that impart light weight, vibration damping, impact absorption, and thermal insulation.

Thermosetting polymers can be joined by mechanical fastening and, to a lesser degree, integral attachment design features or adhesive bonding. Whatever form of mechanical joining is employed, loading must be limited to prevent time-dependent viscoelastic deformation or cold flow, especially in regions of high stress concentration. Adhesive bonding offers the advantage of load spreading, thereby tending to avoid cold flow. Thermosetting-type adhesives are used to join thermosetting-type polymers.

Thermoplastic polymers can also be joined by mechanical means or by adhesives, as well as by two other methods (i.e., solvent cementing and thermal bonding or welding). Within adhesive bonding, solvent cementing is a special process in which a solvent is used to soften (and partially dissolve) a thermoplastic polymer substrate and cause intermixing, setting by evaporation or diffusion of the solvent, and bonding. Welding or thermal bonding is also uniquely possible with thermoplastics, using either external heat sources such as hot plates, hot gas, infrared, induction, radio frequency radiation, or resistance or internal mechanical heating by friction through spin or orbital, linear or vibration, or ultrasonic methods. In the mechanical fastening of thermoplastic polymers, the same precautions must be taken to avoid cold flow as in thermosetting polymers. The use of snap-fit integral attachment design features, relying on the elastic behavior of all polymers and the particular facility with which thermoplastic polymers can be molded, is a rapidly growing method of mechanically joining thermoplastic polymers in a diversity of industries. In adhesive bonding of one thermoplastic to another thermoplastic, adhesives based on thermoplastics must be used.

Elastomeric polymers are special, very long chain molecules that are kinked or coiled in their relaxed state. They stretch to become straight under loading and contract back to their kinked and coiled state upon load removal. These extremely flexible polymers are joined exclusively by adhesive bonding using adhesives that are

themselves elastomers, usually of the same basic type as the polymer(s) being joined. The properties of such adhesives are often achieved by mixing elastomeric with non-elastomeric polymers to create an adhesive alloy.

Rigid plastic foams are always adhesively bonded, and they must be bonded very carefully to prevent collapse of the foam, with the resultant loss of desirable foam properties. Solvent cementing is preferred, although thinned adhesives of the appropriate composition can also be used successfully.

Dissimilar combinations of polymers require the use of adhesive alloys, or mixtures of different types of polymers, if they are to be adhesive bonded, although mechanical joining is also often an option for combinations of dense dissimilar polymers. For example, when bonding thermosets to thermoplastics, an alloy consisting of a thermosetting polymer and a thermoplastic polymer is used.

QUESTIONS AND PROBLEMS

1. Define polymers as materials. What characteristics of polymers lead to their almost unparalleled diversity as materials, allowing them to be so effectively engineered?
2. Develop what is known as a "taxonomy" of polymer types (see Chapter 6, Figure 6.6, as an example in welding), beginning with thermosets and thermoplastics, then dividing into elastomers as a subtype, and into dense and foamed forms for polymers with different chain configuration, stereoisomerism, geometric isomerism, etc.
3. Differentiate between thermosetting and thermoplastic polymers. Give some relative advantages and limitations of each type. Do the same for elastomers within each type.
4. What makes the joining of polymers so challenging? Explain fully.
5. In the broadest or most general sense, what are the options for joining polymers?
6. What are the special challenges of joining thermosetting polymers? What must be considered when such polymers are to be mechanically fastened? What about mechanically interlocked using integral design features? What must be considered when such polymers are to be adhesive-bonded? Which process is generally preferable? Why?
7. What are the special challenges of joining thermoplastic polymers? What must be considered when such polymers are to be mechanically fastened? What about when they are to be mechanically interlocked using integral design features? What must be considered when such polymers are to be adhesive-bonded? Which process is generally preferable? Why?
8. Define the process of solvent cementing. Compare this process to more conventional adhesive-bonding processes and categorize it within the SME classification scheme given in Chapter 5. Compare this process to welding or thermal bonding.
9. List the major types of snap-fit integral attachment features, and briefly describe how each works and under what circumstances each would be a good choice.
10. Describe why thermoplastic polymers can be welded but thermosetting polymers cannot be welded.

11. What are the two broad divisions of welding or thermal bonding processes used for joining thermoplastic polymers? Give some specific examples of processes within each division, as well as some likely applications.
12. What are the special considerations when elastomeric polymers are to be joined? What process(es) would you recommend and why? How would you perform the process(es) differently from how you would for conventional thermosetting or thermoplastic polymers?
13. What are the special considerations when rigid, structural foams are to be joined? What process would you recommend, and how would you think procedures should be modified to ensure success?
14. Explain why dissimilar polymer types must be joined.

Bonus Problems:

A. Why is it that thermosetting polymers cannot be welded, at least in the conventional sense? Are there any possible ways to weld thermosets? Explain your answer.
B. How might polymers be joined by soldering? Under what service conditions or functional requirements would such joining make sense?
C. How are the multiple plies of rubber tires bonded ply to ply?

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Chapter 14

Joining Composite Materials and Structures

14.1 INTRODUCTION

14.1.1 Composites Defined and Classified

Early humans realized that for some uses, combinations of materials often produced properties in the mixed material, or *composite,* that were superior to those of the component materials themselves. For example, mud bricks were reinforced with straw in ancient Egypt, and the warriors of ancient Damascus layered iron and steel in their swords. This represented significant advances in buildings and weapons, respectively, and led to the temporary supremacy of the inventing culture. The advantages of such composite materials and structures have not faded with the passage of time but have grown in use and sophistication. For example, aggregate-reinforced concrete, a simple composite, resulted in improved performance compared to cement, and then steel-reinforced concrete, a more complex composite, resulted in even greater improvements in performance in what is surely the most widely used of all engineering materials. Now, nano-scale[1] particles are leading to unimagined improvements in the properties of ceramics, metals, and polymers of all kinds, and nanotechnology is only in its embryonic state.

All of these materials are composites in the broadest sense, since they all consist of two or more identifiable component materials. This definition, however (i.e., mixtures of two or more identifiable materials to produce a new material), is too broad in one sense and not broad enough in another. A more useful but narrower definition of a composite intended for structural applications (i.e., a "structural composite") is that it is a combination of a structural reinforcing material in a binder or matrix material. The key to this definition is that the component materials act together, in concert, to help one another, often synergistically.[2] An enveloping matrix provides protection from damage

[1] The term "nano-scale" refers to particles with nominal dimensions on the order of 10^{-9} m (i.e., nanometers, nm). The nano-scale is 1,000 times smaller than what is traditionally known as the micro-scale (i.e., on the order of 10^{-6} m, or micrometers, μm). The nano-scale is very close to the scale of atoms (i.e., the atomic scale), as atoms typically have diameters in the range of 0.05–0.25 nm.

[2] *Synergistic* means the action or interaction of two or more substances, organs, or organisms to achieve an effect of which each is individually incapable.

to reinforcements and adds structural stability to the reinforcements under compressive loading. At the same time, the reinforcing material or reinforcement enhances the strength, hardness, stiffness, and/or toughness of the matrix material. As used here, the term *composite* also implies that the component materials remain identifiable and mechanically separable, not merely different at the atomic or molecular level.

But composite materials can offer more than improved mechanical properties, provided the material added to the matrix material imparts something other than mechanical properties. The added material can improve or otherwise intentionally modify electrical properties (e.g., conductivity, dielectric behavior), thermal properties (e.g., conductivity, specific heat), physical properties (e.g., coefficient of thermal expansion (CTE), Poisson's ratio), or virtually any other property. In each and every case, however, the new "composite" material has properties that the component materials do not have alone, rendering the composite unique. The preponderance of applications for composite materials until recently have taken advantage of this ability to custom design or tailor properties to satisfy some unique and often rather specific functional requirements. As such, composite materials are the ideal choice for obtaining functionally specific properties. If needed properties or combinations of properties cannot be found in a single material, they can often be created in a composite, making composites the exemplary "designer material."

The latest embodiment for composite materials is to create what have become known as "smart materials." Some materials have an unusual ability to sense and respond to changes in the environment. When such materials are added to a traditional structural material, the overall composite can adapt to those changes in some desired way. For example, one could add piezoelectric fibers, filaments, or plies to a structural material to sense load-induced strain. Or, because piezoelectric materials as well as magnetostrictive materials react to an imposed electric or magnetic field by exhibiting some strain, these fibers, filaments, or plies of these materials can be used to change the shape of the matrix material. The possibilities for such "smart materials" are endless for sensing and adaptively responding to stimuli (e.g., a laser threat to the skin of a military aircraft, or the water content of paper during its manufacture), or for causing motion (e.g., the movement of the fingers of a prosthetic hand).

The most encompassing definition of a composite material is that it consists of a physical mixture of multiple materials intended to impart functionally specific properties to the whole that are not found in the component materials alone. For the purposes of this treatment on joining, the focus will be on structural composites, but what is said here can be applied to most other types of composites as well.

Composites or composite materials occur naturally but can also be synthesized. This is probably the broadest level of classification—natural versus synthesized composites. Some *natural composites* include rock or stone (a physical, as opposed to chemical, mixture of two or more minerals); wood (a mixture of hard, brittle lignin and softer, tougher cellulose, as well as air entrapped in porous cells); bone (a mixture of hard hydroxyapetite mineral and tough collagen and weight-reducing air); and celery (a mixture of stringy, strengthening cellulose fibers in a pulpy, cellular matrix). Each is structural for its particular need (i.e., to hold earth together or hold up a tree, an animal, or a plant, respectively). Modern synthetic composites include every imaginable

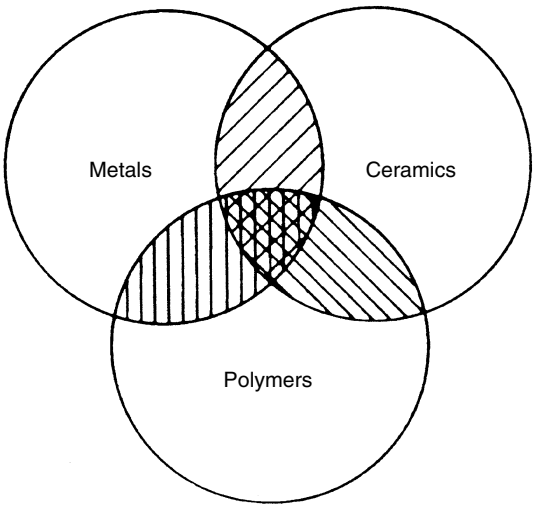

Figure 14.1 Venn diagram showing where composites fit among the fundamental materials of metals, ceramics (and glasses), and polymers. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 14.1, page 478, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

combination of metals, intermetallics, ceramics, glasses, polymers, and carbonaceous materials (e.g., graphite). A simple pictorialization of possible combinations is shown in Figure 14.1 in the form of a Venn diagram. The intersection between any two, as well as among all three, fundamental materials represents a possible composite in which any material could be the matrix that surrounds the reinforcement, which could be any material. It is even possible to have synthetic composites that consist of a physical mixture of two or more metals or alloys, two or more ceramics, etc. In these latter types, as examples: (1) one metal can reinforce another metal as in certain metal-matrix composites (MMCs) (e.g., boron fibers in an aluminum alloy or refractory metal particles or wires in copper); (2) one ceramic can reinforce another ceramic, as in certain ceramic-matrix composites (CMCs) known as ceramic–ceramic composites (CCCs), (e.g., SiC or Si_3N_4 in Al_2O_3 or partially stabilized zirconia or PSZ in SiC); and (3) one polymer can reinforce another polymer as in certain polymer-matrix composites (PMCs) or fiber-reinforced polymers or plastics (FRPs) (e.g., aramid fibers in rubber). In fact, the combinations could become very complex, involving more than three materials, although this is still rare.

In general, synthetic composites are categorized by their matrix material or phase.[3] Major examples include (1) organic- or polymer-matrix composites with either

[3] The common use of the term "matrix phase" can be a misnomer, as the matrix may actually consist of more than one phase, as it would in many reinforced alloys (e.g., aramid fiber reinforced 6061 Al alloy in its two-phase aged condition). Likewise, the so-called "reinforcing phase" can also be a misnomer when it actually consists of multiple phases, as it can if, for example, it was multi-phase alloys, as steel reinforcing rods are in cement or concrete. In steel-reinforced concrete, the reinforcement consists of two phases (e.g., ferrite and cementite), and the matrix consists of many phases (e.g., the multi-phase rock aggregate and the multi-phase cement binder). See Chapter 5, Section 5.5.

thermosetting or thermoplastic matrices and polymeric, ceramic, glass, or metallic reinforcements; (2) metal-matrix composites with polymeric, ceramic, intermetallic, or metallic reinforcements; (3) ceramic-matrix composites with ceramic, glass, metallic, intermetallic, or polymeric reinforcements; (4) relatively new intermetallic-matrix composites with intermetallic, ceramic, or metallic reinforcements; and (5) a special category often included under ceramic composites, carbon–carbon composites, where the matrix and reinforcement phases are simply different forms or grades of carbon. As shown by Figure 14.1, almost every possible combination exists as an engineering material. Examples of most of these are given in Table 14.1.

While the matrix material or phase is used to designate the category of composite, the reinforcement-surrounding matrix tends to give the composite its highest level

Table 14.1 Major Types of Composites (by Type of Matrix and Type and Form of Reinforcement)

Type of Composite	*Type of Matrix*	*Type of Reinforcement*	*Form of Reinforcement*
Natural Composite			
Bone	Collagen	Hydroxyapetite mineral	Extracellular network
Wood	Lignin	Cellulose	Various continuous fibers
Granite	Quartz	Various minerals	Particulate
Organic Composite			
	T/S resin	Glass	p, f(c,d)
		Graphite	p, f(c,d)
		Polymer	f(c), l
		Metal	p, f(c,d), wire
		Ceramic	p, whisker
	T/P polymer	Graphite	f(c,d)
Metal-Matrix Composite	Metal or Alloy	Ceramic	p, f(c,d), whisker
		Intermetallic	p, f(d), l
		Metal	f(c), wire, whisker, l
		Polymer	f(c), l
Ceramic-Matrix Composite	Ceramic	Metal	p, f(c,d), wire, whisker
		Ceramic	p, f(c,d), whisker, l
Concrete	Cement	Ceramic	p (aggregate)
		Metal	bar or mesh
Intermetallic-Matrix Composite	Intermetallic	Intermetallic	p, f(c,d), l
		Ceramic	p, f(c,d), whisker
Carbon–Carbon Composite	Carbon	Carbon	p, f(c,d), l, weave
Engineered Wood	Wood	Wood	l

p = particulate; f = fiber; c = continuous; d = discontinuous; l = laminate

properties (e.g., metallic qualities, ceramic qualities, polymeric qualities). This makes the reinforcing material or reinforcement extremely important, as it usually imparts the functionally specific properties (e.g., strength, hardness, stiffness, toughness, sensing, actuation, etc.). Reinforcements can take the form of (1) randomly dispersed particles (e.g., in particle-reinforced or particulate composites); (2) random or aligned chopped fibers or whiskers[4] (e.g., in fiber-reinforced or whisker-reinforced composites); (3) continuous aligned fibers or wires (e.g., in continuously reinforced composites); and (4) layers or laminations (e.g., in laminate-reinforced composites). These major forms of reinforcements are shown schematically in Figure 14.2. Each form imparts different degrees of anisotropy or directionality of properties, with greater anisotropy occurring with increased alignment of the reinforcing phase.

The advantages derived from combining different types of materials to form synthetic composites are enhanced properties beyond those attainable in monolithic materials, or unique properties unattainable in single, monolithic materials. As stated earlier, the properties being sought are often mechanical and related to structural performance, and include tensile, yield, or ultimate strength and stiffness (modulus).

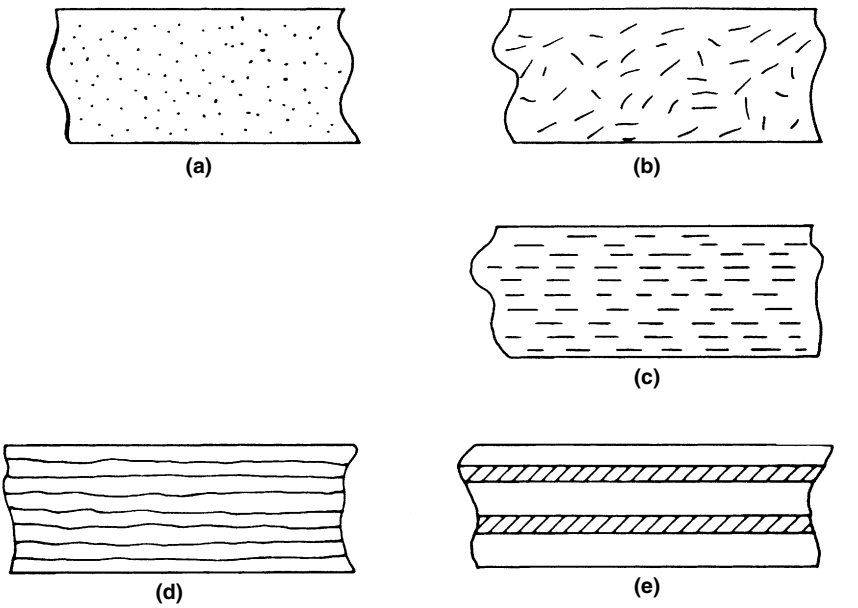

Figure 14.2 Schematic illustration of the various forms of reinforcements found in composite materials. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 14.2, page 479, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

[4] "Whiskers" are single-crystal fibers with a near-perfect structure, often containing only a single, central screw dislocation. As a result, the fibers have phenomenally high strengths, often approaching the theoretical strength of the particular material comprising the whisker.

Of particular interest is the fact that composites offer the possibility of exceptional "specific strength" and "specific modulus," in which "specific" refers to the strength- or modulus-to-density ratio. Plots of the strengths and moduli of a variety of materials versus their densities are shown in Figure 14.3, in which the advantage of composite materials can be easily seen. Figure 14.4 shows a plot of specific tensile strength versus specific tensile modulus for various commercial composites, as well as steel, an aluminum alloy, and alumina for comparison. Composites, however, can be synthesized to obtain other enhanced or unique properties, including (1) improved wear resistance (through addition of a hardening or a lubricating phase); (2) hardness with impact toughness (through the addition of toughening phases to a hard matrix, as occurs naturally in wood); (3) controlled thermal expansion (even zero or negative coefficient of thermal expansion); (4) improved thermal or electrical conductivity or resistivity (depending on need); and (5) enhanced or extended elevated temperature strength. Some examples of the property improvements possible with composites are shown in Figure 14.5 for enhanced elevated temperature performance, and in Table 14.2 for strength and stiffness properties of some important composites versus some important monolithic materials.

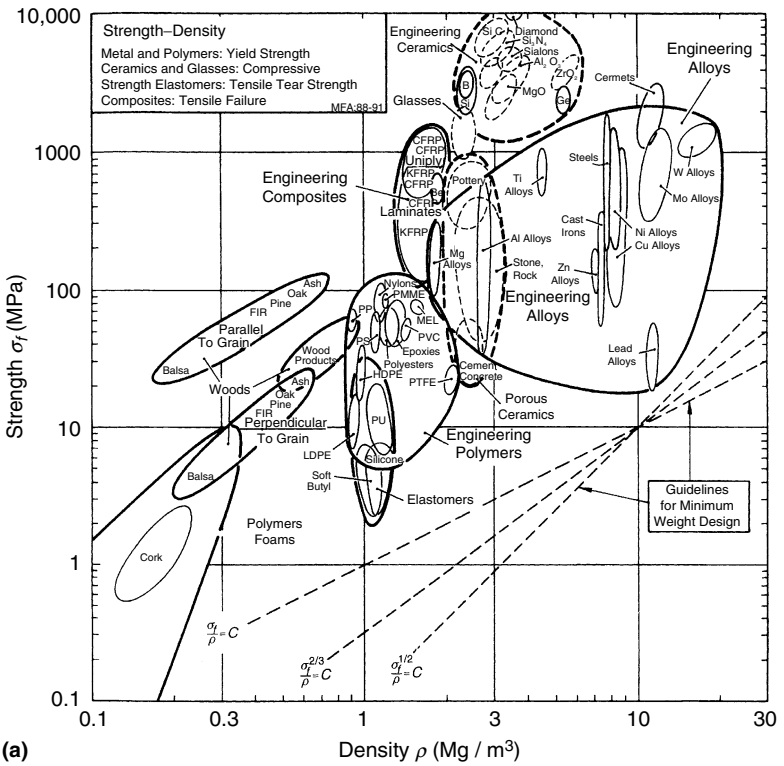

Figure 14.3 Strength versus density (a)

(*Continues*)

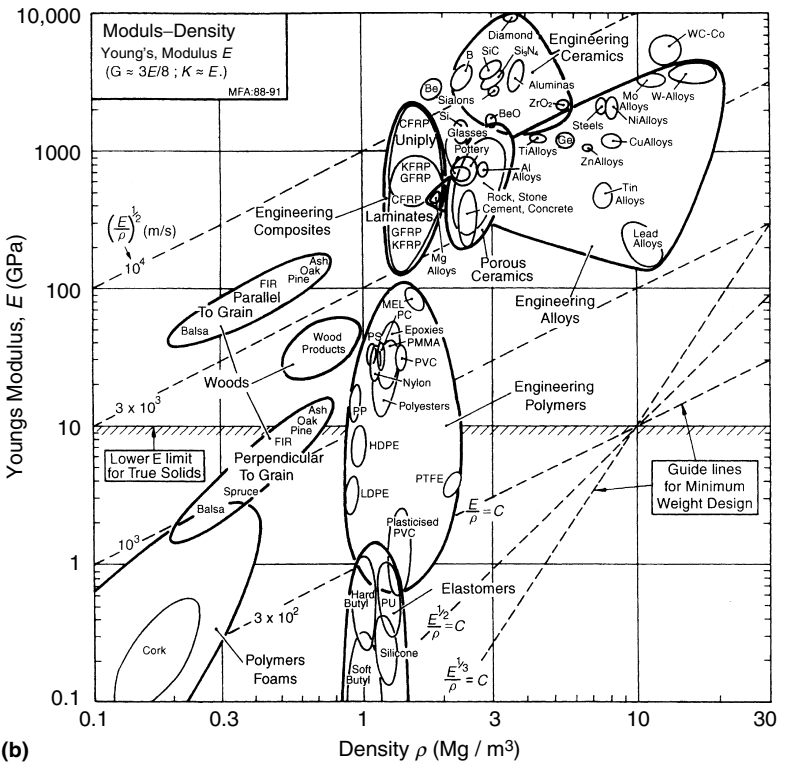

Figure 14.3 (*cont'd*) and modulus versus density (b), showing the superiority of engineering composites. (Reprinted from *Materials Selection in Mechanical Design*, 2nd edition, M.F. Ashby, Figs. 4.4 and 4.3, pages 39 and 37, Butterworth-Heinemann, Oxford, England, 1999, with permission.)

14.1.2 The Special Challenges Posed to Joining by Composites

Joining of composite materials poses a special challenge—how to achieve joint strength or other designed-in functionally specific properties anywhere close to those of the parent composite, since the integrity or continuity of the reinforcement across the joint is difficult or impossible to retain or re-establish. The irony here is that composite materials are usually selected for the exceptional properties they offer to improve performance. Joining is needed to produce the largest and/or most complex and/or most sophisticated structures. The performance of a structure or an assembly is critically dependent on the behavior of any joints it contains, and, as just stated, most contain joints. Hence, the very reason that composite materials may have been chosen in the first place may be lost if effective methods for joining cannot be found.

To join composites, one usually attempts to cause bonding to take place between the matrix materials of the composite joint elements, doing as little damage as possible

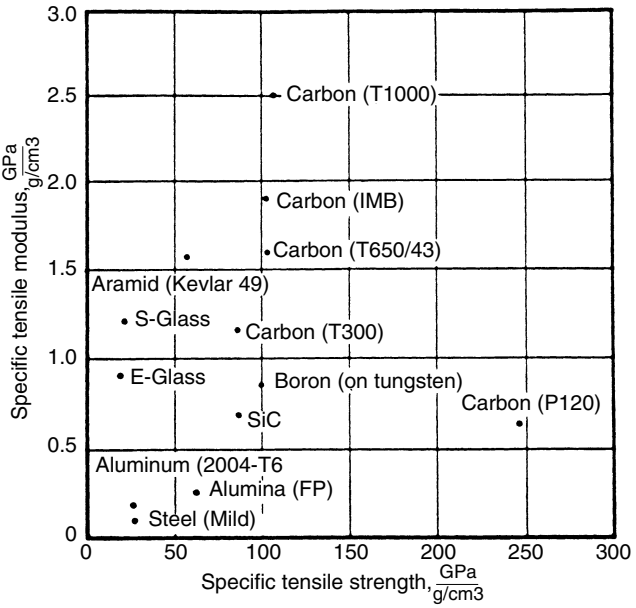

Figure 14.4 A plot of the specific strength versus specific modulus of some important composite materials, as well as some important structural metal alloys and ceramics. (Reprinted from *Fundamentals of Composite Manufacturing: Materials, Methods, and Applications*, A. Brett Strong, Editor, Fig. 4.1, page 88, Society of Manufacturing Engineers, Dearborn, MI, 1989, with permission.)

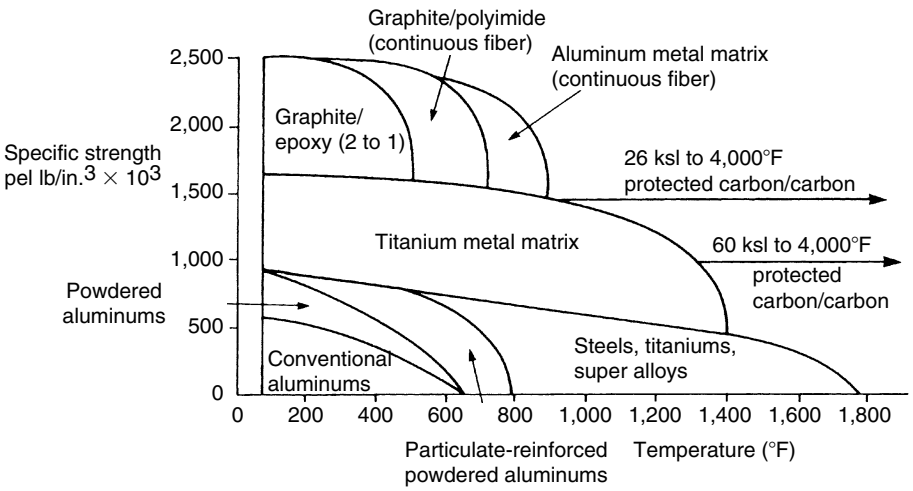

Figure 14.5 A plot of the elevated temperature performance of a number of advanced monolithic versus composite materials. (Reprinted from *Fundamentals of Composite Manufacturing: Materials, Methods, and Applications*, A. Brett Strong, Editor, Fig. 2.12, page 42, Society of Manufacturing Engineers, Dearborn, MI, 1989, with permission.)

Table 14.2 Comparison of the Strength, Stiffness, and Some Physical Properties of Various Composites

Material	*Ult. Ten. Strength MPa*	*Ten. Modulus GPa*	*CTE at 20°C 10^{-6} °K^{-1}*	*Thermal Cond.[a] W/m-°K*	*Density[a] at 20°C g/cm³*
Polymer matrices					
Aromatic copoly., glass fiber (40 vol. %) //	110–114	13–14	–	–	1.70
Bismaleimide, C fiber (68 vol. %) //	1,450–1,500	120–125	–	–	2.0
Bismaleimide, glass fiber (58 vol. %) //	400–450	35–40	–	–	2.3
Epoxy	27.5–90	2.41	35	0.34	1.15
Epoxy, E-glass fiber (73.3vol. %) //	1,640	56	–	–	–
Epoxy, Al_2O_3 whisker (14 vol. %)	779	41	–	–	–
Epoxy, C fiber (67 vol. %) //	1,206	221	–	–	–
Epoxy, Gr fiber (54 vol. %) //	700–1,400	180–220	–	–	1.40
Epoxy, Kevlar fiber (82 vol. %) //	1,517	86	–	–	–
Epoxy, B fiber (70 vol. %) //	1,400–2,100	210–280	–	–	–
Nylon 6/6	75.9–91.5	1.58–3.79	50	0.17	1.10–1.15
Nylon 6/6, glass fiber (43 vol. %) //	140–160	0.85	–	–	1.51
PBT (polybutylene terephthalate)	56.6–60.0	1.93–3.0	40	0.15	1.31
PBT, glass fiber (30 vol. %) //	124–130	5.5–10.0	–	–	1.40
PEEK, glass fiber (20 vol. %) //	149	–	–	–	1.37
PEEK, C fiber (20 vol. %) //	165	–	–	–	1.40
PET (polyethylene terephthalate)	48.3–72.4	2.8–4.1	11.7	0.14–0.15	1.29–1.40
PET, glass fiber (35 vol. %) //	96–100	7.0	–	–	1.60
Phenolic	34.5–62.1	2.76–4.83	20	0.03	1.40
Phenolic, glass fiber (63 vol. %) //	375–400	3.5	–	–	1.90
Phenolic, C fiber (55 vol. %) //	125	16.5	–	–	1.45
Phenolic, Gr fiber (55 vol. %) //	85–90	14.0	–	–	1.42
Polyimide	–	2.07–2.76	27	0.66	1.43
Polyimide, glass fiber (50 vol. %) //	–	10.0–11.0	–	–	1.65
Polysulfone	–	–	31	0.26	1.24
Polysulfone, glass fiber (30 vol. %) //	125	8.5	–	–	1.45
Polysulfone, C fiber (30 vol. %) //	160	–	6.0	–	1.37
E-glass fiber	72.5	3,448	1.3	5.0	2.50
C fiber	210–390	2,400–3,300	8.5–7.0	7.0–10.0	1.78–2.15
Kevlar fiber	131	3,600–4,100	–	60	1.44
B fiber	400	–	–	–	2.57
Wood					
Softwoods	44.8–112	5.5–13.7	–	–	0.31–0.59
Hardwoods	46.9–139	7.0–15.7	–	–	0.35–0.75
Douglas fir, // to the grain	85.5	5.5–15.7	3.0–4.5	0.14–0.16	0.31–0.75
Douglas fir, ⊥ to the grain	~8–10	–	–	–	–
Carbon–carbon: See Table 14.10					
Concrete					
Under compressive loading	37.2–41.4	25–26	10.6–13.5	1.2–1.7	2.4
Ceramic-matrices[b]					
Alumina (Al_2O_3)	275–550	393	6.5–7.6	35–39	3.52
Alumina–alumina, 3D	71.1	30.3	6.4	–	3.5–3.6
Alumina, Gr fiber	–	–	–	–	–
Alumina, Mo fiber/wire	–	–	–	–	–

(*Continues*)

Table 14.2 (*Continued*)

Material	*Ult. Ten. Strength MPa*	*Ten. Modulus GPa*	*CTE at 20°C 10^{-6} °K^{-1}*	*Thermal Cond.[a] W/m-°K*	*Density[a] at 20°C g/cm^3*
Alumina–silica, 3D	71.8	33.8	6.4	–	–
Alumina, stainless steel fiber/wire	–	–	–	–	–
Alumina, W fiber/wire	–	–	–	–	–
Boron nitride–boron nitride, 3D	24.8	15.4	2.7	–	–
Glass, amorphous	69–110	64–69	0.55–3+	1.4	2.0–2.5
Glass, Al_2O_3 fiber	–	–	–	–	–
Glass, Gr fiber	–	–	–	–	–
Glass, Ni fiber/wire	–	–	–	–	–
Glass, SiC fiber	–	–	–	–	–
Glass, W fiber/wire	–	–	–	–	–
Glass–ceramics	123–370	65–120	0.5–8.6	1.3–3.6	2.4–2.7
Glass–ceramic, Gr fiber	–	–	–	–	–
Glass–ceramic, SiC fiber	–	–	–	–	–
Silica–silica, three-directional	26.7	15.6	0.54	–	2.2
Silica–silica, fourdirectional	20.4–26.6	9.7–13.1	0.47	–	2.2
Silicon carbide (SiC)	390–860	129–187	4.2–5.6	71–490	3.1–3.3
Silicon nitride (Si_3N_4)	250–650	200–304	2.7–3.7	10–33	2.3–3.3
Silicon nitride (Si_3N_4), Gr fiber	–	–	–	–	–
Silicon nitride (Si_3N_4), Ta fiber/wire	–	–	–	–	–
Zirconia (ZrO_2)	635	205	10.1	2.9	5.75
Zirconia–zirconia	635	205	–	–	–
Metal–matrices					
Al–alloy, Al_2O_3 particles (10 vol. %)	330	–	–	–	–
Al 2024, B fiber (46–64 vol. %) //	1,460–1,940	220–275	–	–	–
Al 6061, B fiber (51 vol. %) //	1,420	230	–	–	–
Al 2024, Gr fiber (20–40 vol. %) //	520–820	207–558	–	–	–
Al 2124, SiC particles (20–40 vol. %)	–	96.5–144.8	–	–	–
Al 6061, SiC particles (15–40 vol. %)	–	96.5–144.8	–	–	–
Al 7090, SiC particles 20–40 vol. %)	–	103.4–144.8	–	–	–
Al 7091, SiC particles (15–40 vol. %)	–	96.5–139.3	–	–	–
Al 2024, SiC whisker (20 vol. %)	496	109–112	–	–	–
Al 6061, SiC whiskers (20 vol. %)	490–520	108–111	–	–	–
Cu, SiC fiber (23–37 vol. %) //	680–900	172–202	–	–	–
Cu, W wire (50 vol. %) //	1,100–1,260	–	–	–	–
Cu, W p (50 vol. %)	380	190	–	–	–
Mg, Gr fiber (40 vol. %) //	–	172–248	–	–	–
Mg, SiC fiber (34–50 vol. %) //	1,000–1,331	109.6–230.3	–	–	–
Ti–6Al–4V, SiC fiber (35 vol. %) //	1,690	186	–	–	–
Ti–15V–3Sn–3Cr–3Al, SiC fiber (35 vol. %) //	1,572	198	–	–	–
Al alloys	90–503	68.9–72.4	21.1–23.6	100–210	2.68–2.77
Cu	–	11.0	17.7	339	8.84
Mg alloys	160–365	45	25–26	65–76	1.77–1.85
Ti alloys	170–1,103	104–116	9.5–10.0	7.2–15	4.3–4.6

[a]Thermal conductivity (k) and density (ρ) for a composite can be calculated by the ''rule of mixtures,'' using the volume fraction of the reinforcement times the k or ρ for the reinforcement plus the volume fraction of the matrix times the k or ρ for the matrix. [b]For ceramic-matrix composites, flexural strength is used rather than tensile strength or even compressive strength, and fraction toughness is a key property.

to the reinforcing phase. In most cases, no effort is made to join the reinforcing phase. Depending on how reinforcement is achieved in a particular composite (e.g., by dispersed discrete particles, chopped and randomly distributed fibers or whiskers, or continuous, oriented fibers, wires, or laminations) and which specific joining technique is used, some continuity of reinforcement across the joint or within the joint might be possible. More will be said about this at the end of this chapter in Section 14.9. An important clue, however, is that properties in the joint made between composite materials may be either retained (i.e., not adversely affected by joining) or re-established (i.e., restored following joining).

14.2 OPTIONS FOR JOINING COMPOSITES

14.2.1 Historical Approach and General Methods for Joining Composites

As mentioned above, the historical approach to joining composites has been to first deal with the matrix phases, to join those as effectively as possible, and then do as little damage as possible to the reinforcing phases. Very few examples exist of first joining reinforcements and then joining the matrices. However, new and impressive examples do appear in two very different areas, on two very different scales. The first example appears in reinforced concrete, in which any disruption of the reinforced concrete due to damage or necessary excavation is repaired as follows: First, severed steel reinforcing bars are rejoined by fusion welding or wire wrapping, and then the concrete matrix is repoured to harden around the reattached reinforcing bars. The second example appears in limb reattachment. Here, the severed portion of the limb is reattached step by step to the remaining limb. First, bones are rejoined with fasteners and/or adhesives, then major arteries and veins are reconnected by suturing, then muscles, tendons, and ligaments are reattached by suturing, and, finally, nerves are reconnected by suturing. The result is often totally restored function, with the repair containing all of the essential elements of the normal limb. But what is done in these two examples is not what is normally done in joining of composite materials.

Depending on the type (i.e., the matrix) of the composite(s) to be joined, mechanical fastening or integral interlocking, adhesive bonding, welding, brazing, or soldering, as well as some of the variant (e.g., braze welding or thermal spraying) or hybrid (e.g., rivet-bonding, weld-bonding, or weld-brazing) joining processes may be possible.

Generally, for polymer-matrix composites (so-called "fiber-reinforced plastics" or FRPs), there are two basic options, in decreasing order of usage: (1) adhesive bonding and (2) mechanical fastening or integral attachment. For those polymer-matrix composites where the matrix phase is a thermoplastic, welding or thermal bonding is also possible and is being used more often. Weld-bonding of thermoplastic composites is also a viable option, while rivet-bonding is possible with either thermo-setting or thermoplastic composites.

For metal-matrix composites, the most common options for joining are, in approximate decreasing order of usage, (1) brazing, (2) adhesive bonding, (3) mechanical fastening, and (4) welding. Non-fusion welding techniques are rapidly growing in popularity because of the superior properties possible. The hybrid processes of weld-brazing and weld-bonding are also quite common for metal-matrix composites, much more than they are for monolithic metals and alloys. Rivet-bonding is possible, but less common. Intermetallic-matrix composites tend to be brazed or welded since elevated-temperature service is the usual intended application.

For ceramic-matrix composites, including carbon–carbon composites, the primary options are, in decreasing order of preference, (1) brazing and (2) adhesive bonding, with both active metal and ceramic fillers being used in brazing, and inorganic more than organic adhesives being used in adhesive bonding. Welding of ceramic-matrix composites is possible but is still very much the focus of development at this time. Mechanical fastening, as well as mechanical interlocking, is occasionally used.

Table 14.3 summarizes the various options for joining various composites by type.

Regardless of the specific approach used to join composite materials, joint design is critical in composites, perhaps more than in any other material. This is because loading must be carefully controlled to take advantage of any anisotropy and to avoid any problems (e.g., delamination through the thickness of multi-layer or multi-ply composites) associated with these materials, which are also themselves structures.

14.2.2 Mechanical Joining Versus Adhesive Bonding of Composites

For many composites, mechanical joining (especially using fasteners) and adhesive bonding have been and still are the most common methods of joining. Although adhesive bonding is the principal method for joining composites to other composites, to metals, or to various other materials (such as sandwiched honeycomb core), mechanical fastening is used in specific applications where adhesive bonding is not appropriate or optimum.

As is usually the case in joining, the function of the joining material (e.g., adhesive) or device (e.g., fastener or integral interlock feature) is to transfer load from one joint member to the other. The ability to transfer loads depends on the type of load, the environmental conditions, and the materials being joined. Mechanical joining and adhesive bonding each offer different advantages and suffer from different disadvantages.

In mechanically fastened composite joints, advantages relative to adhesive-bonded joints include (1) no special surface preparation of components is needed; (2) there are fewer critical mating or fitup requirements than for bonding; (3) intentional disassembly is possible without damaging the components; (4) inspection is possible by direct observation; (5) resistance to peel or other out-of-plane loading is greater; and (6) sensitivity to thermal, water, and other environmental degradation is lower. On the other hand, relative disadvantages include (1) unavoidable stress concentration from fastener holes or at integral attachment features; (2) possible leaks through open joints or around fasteners; and (3) the weight penalty due to the weight of the fasteners, required inserts, and/or structural stiffeners or doublers.

Table 14.3 Summary of the Various Options for Joining Various Composite Materials by Type (in Approximate Descending Order of Preference)

Continuous Reinforcements	*Discontinuous Reinforcements*
Organic- or Polymer-Matrix Composites	
1. Adhesive bonding (organic adhesives)	1. Fusion bonding (for thermoplastics)
2. Integral mechanical attachment	2. Weld bonding (for thermoplastics)
3. Mechanical fastening	3. Adhesive bonding (organic adhesives)
4. Fusion bonding (for thermoplastics)	4. Mechanical fastening
5. Weld bonding (for thermoplastics)	5. Rivet bonding
Metal-Matrix Composites	
1. Non-fusion welding	1. Non-fusion welding
2. Brazing	2. Fusion welding
3. Weld-brazing	3. Weld brazing
4. Mechanical fastening	4. Brazing
5. Adhesive bonding	5. Mechanical fastening
6. Weld bonding	6. Weld bonding
	7. Adhesive bonding
Ceramic-Matrix Composites	
1. Non-fusion welding	1. Non-fusion welding
2. Ceramic-filler brazing	2. Sinter bonding
3. Metal-filler brazing	3. Fusion welding
4. Cementing (inorganic adhesives)	4. Ceramic-filler brazing
5. Adhesive bonding (organic adhesives)	5. Metal-filler brazing
	6. Cementing (inorganic adhesives)
	7. Adhesive bonding (organic adhesives)
Intermetallic-Matrix Composites	
1. Non-fusion welding	1. Non-fusion welding
2. Brazing	2. Fusion welding
3. Weld-brazing	3. Weld-brazing
4. Fusion welding	4. Brazing
5. Adhesive bonding	5. Adhesive bonding
Carbon–Carbon Composites	
1. Co-bonding (by pyrolizing resin filler)	1. Co-bonding (by pyrolizing resin filler)
2. Brazing	2. Brazing
3. Mechanical fastening	3. Mechanical fastening
4. Adhesive bonding	4. Adhesive bonding

For adhesively bonded joints, advantages compared to mechanically fastened or integrally attached joints include (1) little or no undesirable stress concentration but, rather, favorable load spreading; (2) little or no weight penalty with thin bond lines; (3) smooth external surfaces at the joint (to improve aerodynamic or hydrodynamic flow, as well as aesthetics); (4) freedom from galvanic corrosion in assemblies of dissimilar

materials; (5) facility with thin sections and no risk of fastener edge tear-out or face pull-through; (6) lower sensitivity to cyclic loading due to lower stress concentrations and better strain accommodation; and (7) freedom from fastener bearing problems in matrices prone to cold flow. On the other hand, relative disadvantages include (1) difficult or impossible disassembly without damage to components; (2) susceptibility to environmental degradation by high or low temperatures, water, humidity, salt or salt spray, solvents, biological agents, radiation, vacuum, and ultraviolet light; (3) the requirement for special surface preparation to chemically and physically activate the bonding surface; (4) difficult inspection except by indirect, nondestructive means; and (5) difficult, if not impossible, repair of processing- or service-induced defects.

14.3 JOINING OF POLYMER-MATRIX COMPOSITES

14.3.1 Polymer-Matrix Composites Defined

Polymer-matrix composites are those that have a matrix that is polymeric and reinforcements that can themselves be polymeric (e.g., aramid fiber-reinforced rubber in automobile tires) or can be glass (e.g., fiberglass-reinforced epoxy used in certain automobile body panels or in the hulls and other larger structural components of recreational boats), metals (e.g., steel-wire or mesh-reinforced rubber as used in heavy-duty truck tires), or ceramics (e.g., alumina or cement-filled polymers for more durable floors, etc.). They are commonly referred to as FRPs, when the reinforcements are in the form of fibers (as they often are), although particulate fillers are commonly used for imparting improved wear resistance or insulating qualities. Fibers are often chopped (as they are in fiberglass), but can also be continuous and unidirectional for improved strength and stiffness. To overcome the inherent anisotropy of unidirectional continuous reinforcements, plies or layers of unidirectionally reinforced polymer are typically stacked or laminated with the plies taking various angles (e.g., 0 degrees, 90 degrees, or +/–45 degrees from some assigned axis of the material or part). Such higher performance composites are typically used in aerospace applications, commercial as well as military. Actual laminates are also used as reinforcements in multiple-composite plastic sheets. A close cousin to these is the use of tough, clear plastic sheets laminated between sheets of glass in automobile windshields. The plastic interlayers are intended to prevent glass shards from scattering when windshields are accidentally broken.

Table 14.4 lists important organic- or polymer-matrix composites.

14.3.2 Mechanical Joining of Polymer-Matrix Composites

The use of mechanically fastened and integrally interlocked joints in polymer-matrix composites is a logical carryover or extension from the similar fastening or interlocking of monolithic, isotropic materials such as metals, where a wealth of experience and understanding exists. Designers' enthusiasm for the use of mechanical fasteners with such composites has been tepid, however, due partly to their lack of confidence in the

Table 14.4 Important Organic- or Polymer-Matrix Composites

Reinforcement / *Matrix*	*Glass*[a] *cf*	*chf*	*fab*	*Quartz fab*	*Kevlar cf fab*		*Carbon cf fab*		*Graphite cf fab*	
Thermoplastic Polymers										
Aromatic copolyester	•	•								
Polyamide resins (nylons)	•	•					•			
Polybutylene terephthalate	•	•					•		•	
Polyethylene terephthalate[b]	•	•								
Polysulphone resins	•	•					•			
Thermosetting Polymers										
Bismaleimide	•	•	•				•		•	
Epoxy resins[c] (hi-str./med.T)	•	•	•	•	•	•	•		•	
Phenolic resins (med. T)			•				•	•	•	•
Polyester resins (low T)	•	•								
Polyimide resins (high T)	•	•		•					•	•

cf = continuous fiber; chf = chopped fiber; fab = fabric

[a]There are a variety of glass fibers based on calcium aluminoborosilicate (E) glass, magnesium aluminosilicate (S) glass, and soda–lime–borosilicate (C) glass.

[b]There are also glass–mica chopped fiber combinations.

[c]There are a variety of epoxy resins, as there are a variety of other resins of the other thermoplastic and thermosetting polymers above.

ability of composites to tolerate holes and cutouts. Designers have also sometimes tried to extend joining techniques used for isotropic materials (like metals) to composites without understanding or thinking enough about the anisotropic nature and failure mechanisms of composites. This is not so much the case today because of new understanding.

It is true that FRPs and other directionally reinforced composites can be considerably weakened by the introduction of holes for fasteners. This is, in part, a result of the large tensile elastic stress concentration (K) that occurs in the region of such structural discontinuities. Stress concentration factors can be as high as $K = 8$ in directionally reinforced composites versus $K = 3$ for isotropic materials. It is also partially the result of a lack of plasticity in composites.

In most isotropic materials, plasticity allows yielding to take place in regions of high stress, and the effects of stress concentration on the final net failing stress are thus small. This is not the case for unidirectionally reinforced composites, which are essentially elastic in their behavior all the way to failure. Thus, the effect of stress concentration is to give rise to a low net tensile strain.

One technique used to offset the effect of low inherent plasticity in composites is to reduce the degree of anisotropy in the vicinity of a hole, introducing some softening ("pseudo-plastic" behavior) and thereby increasing efficiency. One specific approach is to incorporate fibers that are oriented in different directions around the holes, while another approach is to employ doublers around holes to reduce the net stress in the section in these areas.

Mechanically fastened joints in composites display the same basic failure modes as do metals (i.e., tension, shear, bearing). Two additional modes of failure are possible

in composites, namely, cleavage and pull-out or pull-through. These modes are shown in Figure 14.6. The failure mechanisms in FRPs, for example, are complex and varied compared to metals and are dependent on fiber or reinforcement type and orientation, surface treatment, joint design, hole quality, and matrix type.

There are several considerations in the mechanical joining of composites, some of which are unique to these special anisotropic materials. These include (1) the materials of the fasteners (to avoid galvanic or anodic corrosion when coupled to highly cathodic reinforcements, like graphite fibers, in a dielectric epoxy); (2) the shape of the fastener head and foot (to spread loading and avoid excessive through-the-thickness loading, which can promote delamination in multi-ply composites); (3) hole size (to ensure proper fit with the fastener); (4) the strength of the fastener; (5) loss of strength because of material being removed by drilling (i.e., destruction of continuous fibers or wires); and (6) joint design. The methods used in the preparation of fastener holes are usually the same as for monolithic materials (i.e., drilling and countersinking), but inserts are frequently used. Also, certain reinforcements (e.g., glass, Kevlar, and graphite) can be highly abrasive to cutting tools, including drills. Holes are often sized to produce interference with the fastener (i.e., the hole is made slightly smaller in diameter than the fastener). This causes the fastener to introduce a compressive residual stress around the hole, which counteracts detrimental tensile stress concentration from applied loads.

The types of fasteners used with composites are essentially the same as those used with monolithic materials, such as metals, but with some special features. Self-tapping screws are rarely used because they are susceptible to thread stripping and pull-out from the inherently soft, low-strength matrix. Rivets are widely used, but larger-than-

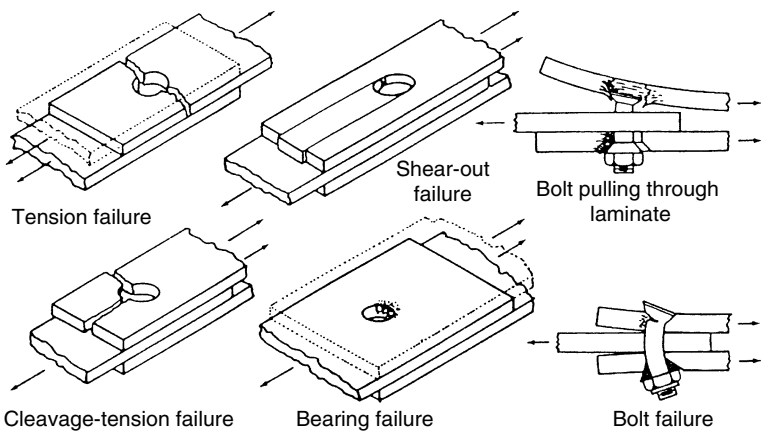

Figure 14.6 Schematic illustration of the various modes of failure for mechanical joints in composite materials. (Reprinted from ''Design of Adhesively Bonded Joints'', L.J. Hart-Smith, in *Joining Fibre Reinforced Plastics*, F.L. Matthews, Editor, Fig. 1, page 230, Elsevier Applied Science, London, England, 1986, with permission of Elsevier Science, Burlington, MA.)

normal heads and feet are employed to distribute loading and avoid cold flow. Bolts are widely used, but also with larger diameter heads and nuts, or with washers under both bolt heads and nuts, and, often, with bushings or inserts. This is all to avoid cold flow from clamping and/or bearing forces and stresses. Finally, pins are used, but usually with hole inserts, bushings, or sleeves to avoid bearing-induced cold flow. As mentioned previously, the type of material used in the fastener must be chosen carefully when graphite-reinforced composites are being joined to avoid preferential galvanic corrosion of the fastener.

The most common types of joint designs used for mechanically fastening composites are shown in Figure 14.7. Various fastener designs and inserts are also shown.

Snap-fit integral attachment features can be used with polymer-matrix composites, just as they are used with monolithic polymers. Molding the small, often complex-shaped interlocking features can be more difficult in composites, depending on the form of reinforcement.

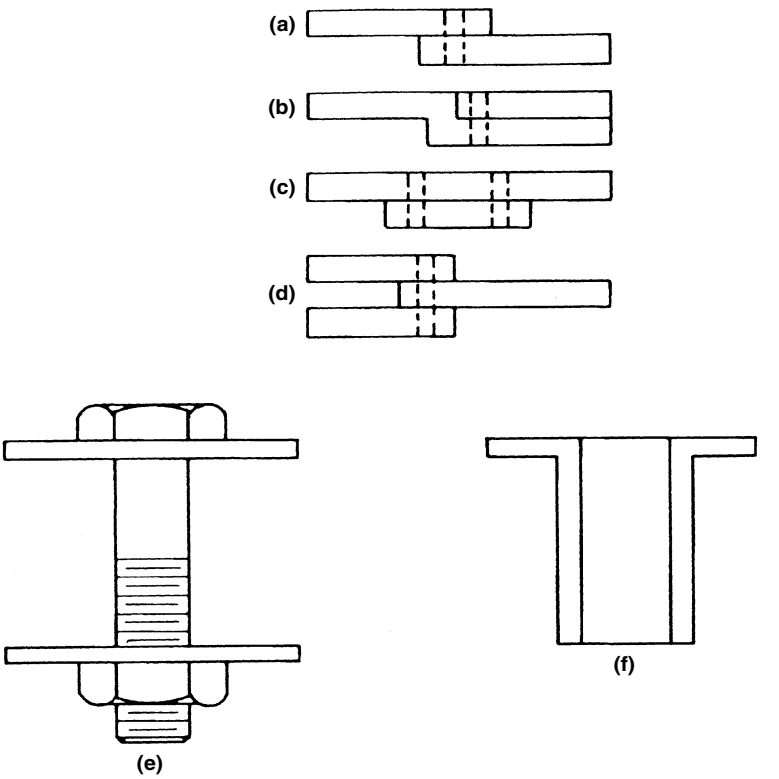

Figure 14.7 Schematic illustration of special joint and fastener designs for use with composite materials. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 14.8, page 487, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

14.3.3 Adhesive Bonding of Polymer-Matrix Composites

The adhesives most often used for bonding polymer-matrix composites are synthetic polymeric adhesives that are generally similar to the matrix of the composite, or mutually compatible with the matrices of mating composites. Thus, thermosetting polymer adhesives are generally used for adhesive-bonding thermosetting-matrix composites (e.g., epoxy–glass), while thermoplastic polymer adhesives are generally used with thermoplastic-matrix composites (e.g., polyetheretherketone (PEEK) graphite). Solvent cementing can also be used for bonding thermoplastic-matrix composites, just as it can be used for bonding monolithic thermoplastics.

Just as epoxies have been the most common matrix for polymer-matrix composites (at least until recently in military aerospace, and still predominantly elsewhere!), epoxy adhesives have also been the most common types used in adhesive bonding. As described in Chapter 5, epoxy adhesives can be either one-component or two-component types. In the one-component types, the curing agent or catalyst is already mixed in, and curing is initiated with heat or UV light. In the two-component types, the user mixes in the chemical curing agent just before adhesive application, and curing occurs by catalysis. The form of the one-component adhesives is usually a sheet; very much like a "pre-preg" (i.e., a fibrous material pre-impregnated with resin) without reinforcement, or it can be a paste. The two-component system must be a paste or liquid.

Room-temperature and elevated-temperature curing adhesive systems are both used in bonding polymer-matrix composites. The room-temperature curing adhesives require post-curing at elevated temperatures to develop good mechanical properties for service at elevated temperatures. Curing times can range from a few minutes for simple, non-critical parts to more than 12 hours for larger, critical performance parts and structures.

Epoxy adhesives have good bond strengths and environmental resistance. Peel strengths are usually poor, however, so elastomeric materials (e.g., rubbers) are often added for "rubber toughening." Examples include butadiene, polyurethane, silicone, and polysulfides. While peel strength is increased over plain epoxy, shear strength is lowered, and sensitivity to moisture and creep (i.e., elevated temperature) is increased.

Thermoplastic materials, which are solid at room temperature, are also used as adhesives for joining polymer-matrix composites, especially those with a thermoplastic matrix. The materials used are called "hot-melt adhesives" because they are melted to become fluid for easy application and then reharden when cooled. Hot melts are most often used with thermoplastics and thermosets when the speed of bonding is important. These adhesives should be avoided when creep is a potential problem, however. Thermoplastic adhesives generally have good peel strength and good environmental resistance, except against organic solvents. As with monolithic thermoplastics, thermoplastic-matrix composites can be adhesively bonded using the method of solvent cementing (see Chapter 13, Subsection 13.4.4).

Specific adhesives for use with thermosetting and thermoplastic composites can be found in Chapter 13, as well as in appropriate references, including those in the bibliographies of Chapter 13 and this chapter.

The effectiveness of an adhesive bond depends on several factors, including (1) the polymeric composition of the adhesive; (2) surface preparation of the adherend(s); (3) adhesive layup procedure; (4) fitting of parts to be joined; (5) tooling; and (6) the curing process. In surface preparation, as discussed in Chapter 5, Subsection 5.6.4, cleanliness (i.e., freedom from contaminants) is critical, and some surface treatment to increase the surface energy and area (i.e., by roughening) is useful.

In critical bond assemblies, a technique called a "mock bond" can be used to assess bond integrity. In this technique, the parts are prefitted and put through a simulated or "mock" bond cycle using adhesive sandwiched between release films (called Verafilm). The parts are then disassembled and the Verafilm^{TM} is inspected to identify areas of poor fit or where extra adhesive may be required.

An adhesive bonding technique that has been proven to be very useful in bonding thermosetting-matrix composite materials to other composites or to metals is to apply the adhesive to the uncured thermosetting composite. Provided the adhesive is chosen to have a cure cycle that is compatible with that of the composite matrix, the composite and the adhesive can be cured together, or "co-cured." This has the obvious advantage of allowing the adhesive and matrix materials to flow together somewhat, making the bond stronger. It also has the obvious advantage of combining processing steps for improved productivity.

The most common types of joints for adhesive bonding polymer-matrix composites or other materials are shown in Figure 14.8. Note that all joint designs for adhesive bonding attempt to force loading to occur in shear to take advantage of the typically higher shear versus peel strength of the adhesive. Whenever possible, simple lap-type joints are preferable, since no machining of the composite pieces is required. This joint type is not as strong as some other types, however, and can result in increased weight due to excess overlap with very little real improvement in strength. As shown in Figure 4.12, more complicated joint configurations, with multiple bond lines, are employed for more demanding applications, including either higher loading or thicker adherends. These more complicated designs basically increase the total bond area and, unfortunately, the manufacturing cost.

One of the problems encountered in adhesive-bonded joints is joint distortion due to bending of thin adherends under eccentric loading and/or the inability of the adhesive to comply elastically or plastically (i.e., the adhesive behaves in a brittle manner). This is shown in Figure 14.9. This problem can be overcome by using more complicated joint designs or stiffeners (see Chapter 4, Subsection 4.6.6).

In all composite joint types, proper composite design would orient the surface fibers in the joint parallel to the direction of loading. The joint itself should be designed and placed to load in shear, avoiding peel or cleavage loading of the adhesive being used for joining as well as between plies.[5] Tapering the edges of joint components helps eliminate stress risers under loading, thus reducing the tendency to peel, especially in

[5] Recall that polymer-matrix composites are often built up from many unidirectionally aligned fiber-reinforced layers or plies. Bonding between plies is, in fact, accomplished by adhesives and is adhesive bonding.

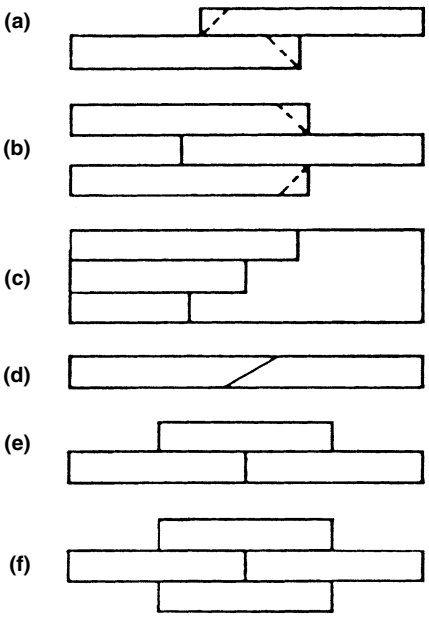

Figure 14.8 Schematic illustration of the common joint designs used for adhesive bonding composite materials. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 14.9, page 489, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

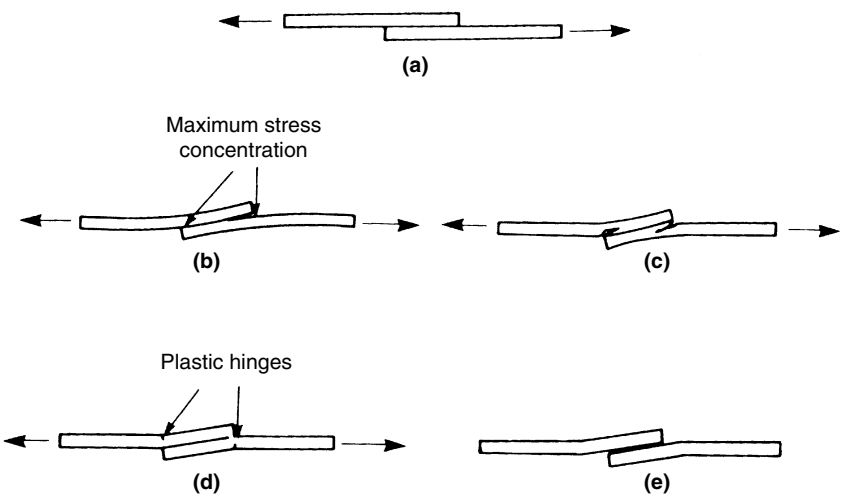

Figure 14.9 Schematic illustration of typical joint distortion in bonded joints. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 14.10, page 490, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

lap joints. Special joint designs using stiffeners also are useful. Again, some of the schemes described in Chapter 4, Subsection 4.6.6 may be useful.

Although not the subject of this book, inspection of joints is key to their proper performance. As pointed out under the disadvantages of adhesive bonding compared to mechanical fastening, inspection of adhesively bonded joints can be difficult. First, inspection must be indirect, as actual bond lines cannot be seen in a plan-view, and, second, joint areas tend to be extensive. Table 14.5 summarizes various nondestructive evaluation (NDE) techniques for assessing the quality of adhesive-bonded composite or other joints. For each technique, the principal characteristic detected, the relative advantages and limitations of the technique, and the types of defects that can be detected are listed.

Figure 1.7 shows two alternative design and fabrication approaches for producing structural subassemblies used on aircraft, here an E2C military aircraft. A conventional all Al-alloy main landing gear door built up by riveting detail parts into an assembly (b) is compared to an upgraded replacement door (a) made up primarily of composite details that have been assembled by a combination of adhesive bonding and some fastening by bolts or rivets, sometimes to Al-alloy fittings. The bonded composite main landing gear door results in dramatically reduced part count (no less fastener count), assembly labor, as well as weight.

14.3.4 Thermal Bonding or Welding of Thermoplastic Composites

When the matrix of a polymer composite is thermoplastic, joining can be accomplished by mechanical joining, adhesive bonding, and welding (or what is referred to as "thermal bonding" in the parlance of the polymer processing community). Thermal bonding methods are described in Chapter 13, Subsection 13.4.5, and so will not be described here. Suffice it to say, welding is accomplished by cleaning the faying surfaces with an organic solvent and/or water and detergent, heating the surfaces to the point of softening (i.e., moderately above the polymer's T_{glass}), and then pressing the surfaces together to effect the bond. In addition, conventional heating methods (e.g., hot platens, hot gas, or infrared sources), frictional or vibration heating, including ultrasonic heating, and induction heating (which requires a metal screen insert called a "susceptor") can be used to effect welding.

Welding or thermal bonding of thermoplastic-matrix composites may or may not require the use of a filler material. If the entire laminate gets hot enough for the surface fibers of an FRP to deform and intermingle with those of the mating surface, excess resin is usually not required. If this does not occur, additional resin (usually of the same type as used in the matrix of the composite) may be added by any one of several means (e.g., sheets, powder, solvent-softened paste). Additional resin is often required in structurally reinforced composites during ultrasonic, friction, vibration, or induction welding.

Joint strengths achievable by welding or thermal bonding can be quite high, approaching the strength of the parent material comprising the joint elements, even when that material is a composite.

Table 14.5 Summary of NDE Techniques for Quality Assessment in Adhesively Bonded Joints

	Radiography	*Ultrasonics*	*Acousto-ultrasonics*	*Acousto Emission*	*Thermography*	*Optical Holography*	*Eddy Current*
Principle/ characteristic detected	Differential absorption of penetrating radiation	Changes in acoustic impedance caused by defects	Uses pulsed ultrasound stress wave stimulation	Defects in part stressed generate stress waves	Mapping of temperature distribution over the test area	3-D imaging of a diffusely reflecting object	Changes in elec. cond. caused by material variations
Advantages	Film provides record of inspection; extensive database	Can penetrate thick materials; can be automated	Portable, quantitative, automated, graphic imaging	Remote and continuous surveillance	Rapid, remote measurement; need not contact part; quantitative	No special surface preparation or coating required	Readily automated; moderate cost
Limitations	Expensive; depth of defect not indicated; radiation safety	Water immersion or couplant needed	Surface contact, surface geometry	Requires application of stress for defect detection	Poor resolution for thick specimens	Vibration-sensitive if not coupled	Limited to elec. cond. materials; limited penetration depth
Defects detected							
Voids	Yes	Yes	Yes	No	Yes[b]	Yes	Yes
Debonds	Yes[a]	Yes	Yes	Yes	Yes[b]	Yes	Yes
Delaminations	Yes[a]	Yes	Yes	Yes	Yes[b]	Yes	Yes
Impact damage	Yes[b]	Yes	Yes	Yes	Yes[b]	Yes	Yes
Density variations	Yes	Yes	Yes	No	No	No	Yes

Resin variations	Yes	Yes	Yes	No	No	No	Yes
Broken fibers	Yes[c]	Yes	Yes	Yes	No	Yes	Yes
Fiber misalignment	Yes	Yes	Yes	Yes	No	No	Yes
Wrinkles	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Resin cracks	Yes[b]	Yes	Yes	No	Yes	Yes	Yes
Porosity	Yes	Yes	Yes	No	Yes[b]	Yes	Yes
Cure variations	No	Yes	No	No	No	No	Yes
Inclusions	Yes	Yes	Yes	Yes	No	No	Yes
Moisture	No	Yes	Yes	No	Yes	Yes	Yes

[a]Should be physically separated. [b]Minor damages may not be detected. [c]Might give problems.

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Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 491, Table 14.3, 1993), with permission of Elsevier Science, Burlington, MA.

14.3.5 A Radical Idea for Joining Thermosetting Composites

A recent paper (Messler, 2003) describes some thought-provoking possibilities for joining polymer-matrix composites. One of these, worth mentioning for the difficult and heretofore unsuccessful "welding" of thermosetting-matrix composites, is called "moving boundary curing" or "moving boundary joining." Conceptually, this method causes a joint to be formed between two (or more) as-yet-uncured thermosetting polymer-matrix composites by co-curing the joint elements while they are in contact. While this, by itself, is not novel, what is novel is the concept of causing curing to take place from the inside (i.e., center) to the outside (i.e., surface) of thick section joint elements. As shown schematically in Figure 14.10, embedded "cure-initiating elements" cause the reaction to begin in the deepest portion of a thick section and propagate outward in a controlled fashion. This prevents the exothermic heat of the curing reaction from causing overheating, as occurs when such thick sections are cured from outside to inside by conventional radiant heating (e.g., irradiating lamps or heating elements), convection heating (e.g., using hot air, gas, or steam), or conduction heating (e.g., using heated press platens). A computer-based model of heat transfer would be used to control the reaction front, causing it to sweep through the joint, either from the center outward or from one side of the joint to the other.

While it has been tested only on very small joints, and needs much more development, the technique is intriguing.

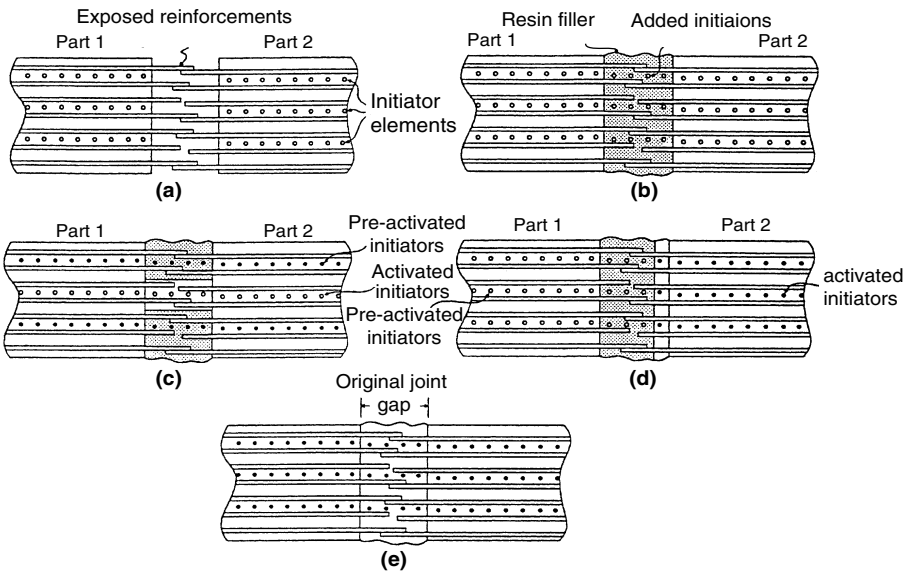

Figure 14.10 Schematic illustration of the novel concept of moving boundary curing and/or joining for thick-section thermosetting-matrix composites. (Courtesy of the *Journal of Thermoplastic Composite Materials*, with permission of Sage Publications, London, England.)

14.4 JOINING OF METAL-MATRIX COMPOSITES (MMCs)

14.4.1 Metal-Matrix Composites (MMCs) Defined

Metal-matrix composites (MMCs) consist of high-performance reinforcements in a continuous metallic matrix. The reinforcements can be in the form of particles (on a microscopic- or, quite recently, nano-scale), whiskers, chopped (i.e., discontinuous) or continuous fibers or wires,[6] or even laminates. They can be metallic, intermetallic, ceramic, or polymeric. Whiskers and discontinuous fibers can be random or oriented, while continuous fibers or wires and laminates are always oriented or aligned. Particles, whiskers, and chopped fibers are virtually always uniformly distributed through the matrix, while laminates might not be.[7] Metal matrices can be almost anything, but some typical ones are aluminum or aluminum alloys (e.g., with Al_2O_3 particles or Al_2O_3–sapphire fibers or whiskers; SiC particles, fibers, or whiskers; boron (B) fibers; graphite fibers; aramid fibers or laminates; titanium or titanium alloys (e.g., with Al_2O_3, SiC, Si_3N_4, B, SiC-coated B or "borsic," TiB_2, and graphite or TiC fibers); magnesium or magnesium alloys (e.g., with graphite fibers); and copper (e.g., with Mo, W, WC, or graphite particles, fibers, or wires). There have also been some refractory metal (e.g., Mo, W, or Nb) wire-reinforced Ni-base superalloys, and there are so-called "oxide dispersion-strengthened" Fe- and Ni-based superalloys known as "ODS alloys." Most recently, intermetallic (e.g., Ni-aluminide and Ti-aluminide) reinforced Ni- and Ti-based alloys have begun to appear in development. Table 14.6 lists some common and emerging metal-matrix composites by matrix.

Metal-matrix composites can offer a variety of significant property advantages over unreinforced, monolithic metals and alloys, depending on the material and form of the reinforcement. Modulus and strength, in both tension and compression (to resist buckling), can be increased up to 100% with discontinuous reinforcements and much more with unidirectional, continuous reinforcement. Dynamic damping capacity is almost always increased (up to five times) because of scattering and attenuation, regardless of the form of the reinforcement. But there is clearly more damping in larger matrix-reinforcement interface areas. The coefficient of thermal expansion can be tailored to need (i.e., adjusted to a particular value), including being made zero or even negative in one particular direction. Wear resistance is usually increased by the addition of hard phases (e.g., ceramics or intermetallics), but often at the expense of machineability. Fatigue strength of the material as well as structural damage tolerance are usually increased by absorbing the energy at the tip of a propagating crack,

[6] The difference between wires and fibers is one of size, with fibers tending to be smaller than about 0.25 mm (0.010 in.) in diameter and wires being larger than that.

[7] In fact, there was some work done in military aerospace to selectively reinforce structures by applying reinforcing materials, usually in the form of strips of composite, to specific areas of the structure (e.g., longitudinally at the location of maximum compressive and tensile bending around a landing gear).

Table 14.6 Common and Emerging Metal-Matrix Composites

Matrix *Reinforcement*	*Al*	*Mg*	*Ti*	*Zr*	*Be*	*Cu*	*Ag*	*Ni*	*Co*	*SA*[a]	*Nb*	*Mo*
Al_2O_3 (p,wh,f)	•	•	•	•	•	•						
B(f)	•	•										
BN(f)	•											
BorSiC(f)	•		•									
$Carbon_{graphite}$(f)	•	•	•	•		•		•				
SiO_2 (p,wh,f)	•											
Vitreous silica (f)	•	•										
Glass (f)	•											
SiC (p,wh,f)	•	•	•	•	•	•		•	•	•	•	•
Si_3N_4 (p,f)	•		•									
NbC[b]								•	•	•	•	
TiC[b]								•	•			
TaC[b]								•	•			
HfC[b]								•				
WC (p)						•	•		•			•
ThO (p)								•				
Ni_3 Al (f)								•	•	•		
Ni–Cr–Al–Y (f)								•		•		
Be (f,w)	•	•	•	•		•						
Stainless steel (w)	•							•				
W (w, or p in Cu)						•		•		•	•	•
Mo (w)			•							•		
Ta (w)		•								•		
Nb (w)						•	•	•	•	•		

[a]SA = Superalloy.
[b]*in situ*; p = particulate; wh = whisker; w = wire; f = fiber
Adapted and updated from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Stoneham, MA, Butterworth-Heinemann, page 493, Table 14.4, 1993, with permission of Elsevier Science, Burlington, MA.

relieving the stress concentration by crack-tip blunting, and arresting further growth. Anisotropy of most mechanical and physical properties can be controlled, either to minimize directional effects (i.e., approach isotropy) or, more logically, to take advantage of these unique materials, to tailor effects for specific directional properties or damage tolerance. In one important application area, tough reinforcing materials are being added to metallic alloys to provide ballistic protection (i.e., to create armor). Finally, use temperature can be extended through the use of refractory (e.g., metal, intermetallic, or ceramic) reinforcements (see Figure 14.5).

14.4.2 General Requirements for Joining MMCs

The high inherent thermal conductivity and serviceability of metals and the extension of their strength to higher temperatures through reinforcement by appropriate

materials (e.g., refractory metals, intermetallic, or ceramics) often dominate property requirements when MMCs are selected and used.[8] Thus, when MMCs need to be joined, the joining process must result in adhesion that can tolerate elevated temperatures and preserve the reinforcement across the joint as much as possible. Of course, there are applications for MMCs that do not require elevated temperature serviceability, so other joining options open up.

Preferred methods for joining metal-matrix composites are, in approximate decreasing order of preference for elevated-temperature serviceability (1) welding, (2) mechanical fastening, (3) brazing, and (4) adhesive bonding (particularly for polymer-reinforced metals for non-thermal applications). Welding allows service temperatures to approach the melting temperature of the lowest melting joint component or the mixed-weld metal. Brazing allows service temperatures up to the limit of the service temperature of the braze alloy. If diffusion brazing is used, this can be quite high, approaching the melting point of the lowest melting base metal in the joint. Mechanical fastening can allow service to near the melting temperature of the joint element composite's matrix, or to the limiting service temperature of the reinforcement, or to the limiting service temperature of the fastener's material, whichever is lowest. Adhesive bonding would rarely be used with MMCs unless they were selected for one of their special physical or mechanical properties other than service temperature, for example, controlled CTE or ballistic impact resistance.

14.4.3 Welding MMCs

Whether a metal-matrix composite is being welded to another metal-matrix composite of the same or different type or composition or to a monolithic metal of similar or compatible composition to the matrix, the preferred welding processes will (1) preserve the integrity of the reinforcement, often by avoiding or minimizing melting or even severe heating of the matrix; (2) minimize exposure of the reinforcement to elevated temperatures during welding to prevent the occurrence of degrading reactions between the reinforcement and the matrix; and (3) minimize forces that could compromise the integrity of whiskers or continuous-fiber reinforcements (e.g., high localized pressure such as from resistance welding electrodes, or from plastic upset such as from friction or inertia welding). The trick is to cause primary metallic bond formation between matrices or between the matrix and a metal component, with as little melting and at as low a temperature and for as short a time as possible. Thus, preferred welding processes are, in descending order of preference: (1) non-fusion welding processes, (2) resistance welding processes, (3) high energy density beam processes, and (4) low net linear heat input processes, all because heating rates are very fast. Viable options are (1) inertia, friction, ultrasonic, and diffusion welding; (2) resistance spot and seam

[8] There surely are other applications for which MMCs are selected, but many of these also demand good elevated temperature—or related—behavior. One example is the reinforcement of high-conductivity pure copper with refractory metal particles, fibers, or wires to improve the resistance of resistance spot-welding electrodes to erosion by arcing or sparking.

welding and, especially, capacitor-discharge (percussion) welding; and (3) laser and electron beam welding. Gas–tungsten arc and plasma arc welding have also been used with limited success, provided the net linear heat input can be kept low, perhaps by pulsing current.

In non-fusion as well as in resistance welding, the amount of melting is either nonexistent or minimal, respectively. For all except diffusion welding (DFW), the rates of heating are quite rapid, the times at peak temperature are quite short, and post-weld cooling is rapid; all of these factors minimize the time available for adverse reactions to occur. In diffusion welding, the actual bonding temperature might be able to be kept low enough to avoid excessive thermal damage to the reinforcements, especially if special diffusion barrier coatings are used on fibers (e.g., silicon carbide on boron in what are known as "borsic" fibers). In resistance welding, the heating cycle is specially designed to melt a nugget and create a bond with minimal melting and minimal upsetting to avoid physically breaking brittle fibers. In laser beam welding, the matrix can be made to melt rapidly and very locally, and melting, vaporization, or other thermal degradation of the reinforcements may be avoidable if short, high-energy pulses are used. In electron beam and in continuous mode laser beam welding, the intensely high energy density of the process usually causes vaporization (i.e., key-holing), so fiber damage is to be expected in the actual region of fusion. Total heat input is low, however, so thermal damage to the reinforcements outside the fusion zone is minimized.

Capacitor-discharge welding has produced some excellent welds in some MMCs, most notably SiC-reinforced aluminum alloys. In the capacitor-discharge or percussion resistance welding process, rod-to-rod or rod-to-plate welds are made by causing arcing and subsequent melting and matrix softening by discharging a bank of capacitors across a gap between the parts to be welded. Gravity, sometimes assisted by a spring, is used to move the parts together during arcing. As the components meet, the arc is extinguished, solidification occurs, and excess molten metal is expelled from the joint. Heating and subsequent cooling are very rapid, minimizing time at temperature.

Exactly how susceptible the reinforcement of a metal-matrix composite is to damage by heat and/or pressure of a welding process depends on the material and the form of the reinforcement. If the difference in melting temperatures between the matrix and the reinforcement is great, with the reinforcement being much more refractory, the heat of welding for many processes (including certain fusion processes such as GTAW or PAW) will likely cause little or no problem. When the melting temperatures are closer, or the reinforcement is inherently highly reactive with the matrix, or vice versa, the heat of welding can cause degradation of the reinforcement properties outright or through adverse chemical reactions between the reinforcement and the matrix. The reaction product is often inherently brittle, so it degrades adhesion between the matrix and the reinforcement by constituting a weak boundary layer (see Chapter 4, Subsection 4.3.4). Another common problem encountered during fusion welding of MMCs is severe outgassing and porosity formation in both the fusion zone and the high-temperature heat-affected zone or partially melted zone of the weld. If the reinforcement is inherently resistant to thermal degradation of its

properties but is reactive with the matrix, a diffusion barrier coating can be applied to the reinforcements. This is done on silicon carbide fibers intended for use in reinforcing titanium or its alloys. Proprietary coatings are applied to boron fibers in so-called "borsic" fibers.

Susceptibility to damage by the pressure associated with some welding processes, especially so-called "pressure welding processes" such as resistance, inertia, or friction welding, is greatest with continuous fibers, troublesome with whiskers, less serious with chopped fibers, and essentially no problem with particulates or dispersoids. Short discontinuous fibers and particulate reinforcements, if suitably refractory, may survive some fusion processes, provided vaporization from key-holing does not occur. Examples are alumina and yttria particle reinforced matrices in aluminum- or nickel-based alloys, respectively.

Table 14.7 lists the major welding processes that have been successfully used to join MMCs.

14.4.4 Brazing MMCs

Brazing can be an attractive option for joining MMCs because no melting of the matrix occurs. Thus, degradation of reinforcements is usually minimal, especially if the reinforcement is reasonably refractory. Brazing MMCs to one another or to monolithic metals is accomplished using fillers that are compatible with the metals or alloys involved. In most cases, time at temperature should be minimized, so processes that localize heating to the area being brazed are preferable. For maximum temperature serviceability (provided the reinforcement is suitably refractory and non-reactive), diffusion brazing offers the best choice, as the remelt temperature of the braze proper is increased by interdiffusion between the filler and the matrix.

Table 14.7 List of Welding Processes Successfully Used for Joining Metal-Matrix Composites

Matrix			*Al*			*Mg*		*Ti*		*Cu*	
Reinforcement	*B*	*Gr*	*SC*	*AO*	*Gr*	*SC*	*Gr*	*SC*	*Gr*	*W*
DFW							•	•	•	•
FRW	?	•	•	•	•	•	?	?	•	•
FSW (discontinuous reinforcements)			•	•			?	•	?	?
RSW	•	•	•	•	•	•				
PEW (by capacitor discharge)	•	•	•	•	?	?				
LBW	•	•	•	•	•	•	•	•	•	•
EBW	•	•	•	•	?	?	•	•	•	•
PAW		?	?	•			•	•		
GTAW		•	•	•					•	•

B = boron; Gr = graphite; SC = silicon carbide (SiC); AO = alumina (Al_2O_3); W = tungsten

It is conceivable that particulate or even discontinuous (chopped) fibers or whiskers could be added to the braze filler so that the braze filler itself is also reinforced, but this has actually been done only on a limited basis.[9]

14.4.5 Mechanically Fastening or Integrally Attaching MMCs

Metal-matrix composites can be mechanically fastened using threaded or unthreaded fasteners, or can be mechanically attached using designed-in interlocking features, although this is still rare. As with all composites, care must be taken in placement of any fastener holes to avoid or minimize damage to continuous fiber reinforcements. Reinforcing materials in any form can be abrasive, making hole drilling and finishing difficult and accelerating tool wear. Often, special joint designs soften the areas to be drilled to accept fasteners, eliminating reinforcements in those areas or employing inserts. Deciding on preload can be made especially difficult by the composite's properties.

14.4.6 Adhesive Bonding MMCs

Since organic or polymeric adhesives have very limited temperature serviceability, and since inorganic adhesives tend to not develop very high adhesion with metals, adhesive bonding of MMCs is unusual because these materials are often selected for their tolerance of high temperatures. For applications that do not involve high temperatures, but for which certain other properties of an MMC are desirable, adhesive bonding is, of course, possible. Such applications might include use of MMCs to provide resistance to ballistic impact and penetration (i.e., as armor, for vibration damping, or, increasingly, for incorporating sensors and/or actuators that operate based upon some interesting physical phenomenon found in the "reinforcement"). Examples of such interesting physical phenomena include shape memory effect (in which a material can be caused to return to a preset shape or dimension from a modified shape or dimension due to a massive, shear-based martensitic transformation); piezoelectric behavior (in which a material gives off a voltage in response to an applied strain; dimensional changes under the application of an applied voltage); and others. Hence, MMCs being used as "smart materials" can be successfully and often appropriately joined by adhesives.

The choice of adhesive for bonding is based solely on the matrix material. Provided an adhesive is compatible with the monolithic form of the matrix material, it will be suitable for the MMC. Adhesive options for various matrix materials can be found in Table 5.4 in Chapter 5. To bond metal-matrix composites, one merely needs to select an adhesive that is compatible with the metal as an adherend.

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[9] This approach is not unusual in so-called "hard-facing" using welding. Fine particles of WC are often added to braze fillers to improve wear resistance.

14.5 JOINING OF CERAMIC-MATRIX COMPOSITES (CMCs)

14.5.1 Ceramic-Matrix Composites (CMCs) Defined

A ceramic-matrix composite (CMC) has a matrix that is neither organic and resinous (i.e., polymeric) nor metallic. Generally, ceramic matrices are solid, inorganic, nonmetallic materials that contain positive and negative ions (i.e., cations and anions) that are ionically bonded, or mixed metal and nonmetal atoms that are covalently bonded. Mixed ionic and covalent bonding is also possible for certain elemental species. The solid material may be crystalline, non-crystalline (i.e., vitreous or glass-like), or mixed (i.e., partially crystalline with a glassy phase surrounding a crystalline phase as a binder). CMCs are characterized by high strength, high hardness, high stiffness, refractoriness, and exceptional chemical and thermal stability, just like their monolithic ceramic cousins. Unlike their ceramic cousins, CMCs offer improved toughness, usually through the incorporation of the reinforcing phase, which can be metallic, ceramic, intermetallic, or even polymeric. Reinforcements can be in the form of micro- or nano-scale particles, discontinuous or continuous fibers or wires, or laminates.

Toughness is obtained in CMCs by any of several possible mechanisms, including (1) strain-induced phase transformation of the reinforcing phase to produce a compressive residual stress due to increased specific volume after transformation (e.g., partially stabilized zirconia); (2) arrestment of a propagating crack in the inherently brittle ceramic matrix by inherently tough reinforcements that are well bonded to the matrix phase (e.g., certain soft, tough metals or most polymers); or (3) arrestment of a propagating crack in the inherently brittle matrix by dissipation of energy and crack tip blunting and/or propagation direction change by an intentionally weak reinforcement-matrix interface.

Table 14.8 lists some important metal- and ceramic-reinforced ceramic-matrix composites.

14.5.2 General Methods for Joining CMCs

The preferred methods for joining ceramic-matrix composites depend principally on the material of reinforcement, since this material largely affects temperature serviceability because of its inherent melting temperature or its reactivity with the matrix upon heating (which is usually minimal because the ceramic is already in an oxidized state). This is obviously (but not unreasonably) premised on the choice of a CMC for its particular suitability to elevated-temperature service. Another important consideration, however, is matching coefficients of thermal expansion (i.e., CTEs). CMCs have been used in armor, but little has appeared in the open literature, for obvious reasons of military secrecy.

The lowest temperature serviceability is unquestionably that of polymer-reinforced ceramics, which are currently by far the rarest type. In fact, these composites, to date, are more often ceramic-filled or reinforced polymers than actual polymer fiber or laminate. Examples are talc- ($Mg_3Si_4O_{10}(OH)_2$) or calcium carbonate- ($CaCO_3$)

Table 14.8 Important Metal- and Ceramic-Reinforced Ceramic-Matrix Composites

Matrix / *Reinforcement*	*AO*	*ASO*	*B_4C*	*CrO_2*	*Glass*	*AO/SO*	*Si*	*SO*	*SC*	*SN*	*ThO*	*TiC*	*ZrO_2*	*NiO*
Al_2O_3 (f)					•				•	•		•	•	
Graphite (f)	•				•				•	•				
CaO														•
MgO	•						•		•					
Mullite												•		
SiC	•						•			•			•	
Si_3N_4									•			•		
BeO	•								•					
BN	•		•					•						
ZrO_2	•													
PSZ[a]	•										•		•	
Cr		•		•									•	
Ni											•		•	
Nb		•		•									•	
Ta		•		•									•	
Mo	•		•	•		•							•	
W	•		•	•		•							•	

$AO = Al_2O_3$;$ASO = (Al, Cr)_2O_3$;$AO/SO = Al_2O_3 + SiO_2$;$SO = SiO_2$;$SC = SiC$;$SN = Si_3N_4$
[a]= Partially-stabilized zirconia; f = fiber

filled epoxies. More recently, however, true polymer-filled cement and concrete have received attention as tough, seismic vibration-tolerant masonry construction materials. For the former group, adhesive bonding using polymeric adhesives is preferred, matching the adhesive to the ceramic adherend (see Table 5.4, Chapter 5). For the latter group, similarly toughened cement is used as the inorganic adhesive to provide toughness in joints as well as in the joint elements.

Metal-reinforced ceramics, formerly and still commonly referred to as "cermets," are usually designed for wear resistance with toughness. Their applications include cutting tools but have increasingly been considered for—and been used in—other demanding applications, such as advanced ceramic heat engines, ballistic armor, and electronics. The preferred methods for joining are, in decreasing order of popularity brazing, cementing or mortaring with inorganic adhesives, and adhesive bonding with synthetic, polymeric adhesives. Brazing generally offers the highest temperature serviceability, with the limit being set by the metallic braze filler alloy or by thermal mismatch between the metallic filler and the predominantly ceramic matrix. Bonding with inorganics, as in cementing and mortaring, can offer excellent service temperatures, depending on the specific material used as the adhesive. Fired cements offer the highest temperature serviceability of all. Bonding with organic adhesives is most temperature-limited but can be useful for nonthermal applications (e.g., electronics and opto-electronics).

Ceramic-reinforced ceramic–ceramic composites (or CCCs) offer the greatest refractoriness and are often designed and selected for the most demanding of these applications. As a result, the preferred joining processes are welding, brazing, and cementing or mortaring. Welding can be by either non-fusion (e.g., friction welding or diffusion welding) or fusion welding processes (e.g., high energy density LBW or EBW). Joint strength and temperature serviceability can both be excellent, provided welds can be made that are free of cracks. Brazing can be accomplished using either a metallic or a ceramic filler, with the ceramic filler having greater temperature serviceability. As for metal-reinforced ceramics, cementing and mortaring can produce excellent joints of quite good temperature serviceability if the cement or mortar is fired.

Two other options actually exist for joining CCCs during their fabrication (1) sinter bonding and (2) self-propagating high-temperature synthesis (SHS), combustion synthesis (CS), or thermite[10] synthesis. Both of these rely on bonding by diffusion, with varying amounts of liquid phase present. Sinter bonding was described in Chapter 12, and self-propagating high-temperature synthesis was described, as exothermic brazing, in Chapter 7. Both processes offer great potential for joining CCCs.

14.5.3 Direct Bonding of Ceramic–Ceramic Composites (CCCs)

Without question the best joint integrity in ceramic–ceramic composites, or CCCs, is obtained by direct bonding[11] during the initial production of the composite. Two methods are available, depending on the method used to produce the composite in the first place: (1) self-propagating high-temperature (SHS), or combustion synthesis (CS) and sinter bonding.

In SHS or CS, CCCs of oxide-carbide types are made by reducing oxides in the presence of carbon. The resulting reaction is highly exothermic, and the heat generated propagates through the ceramic composite body. Joining can be accomplished by placing the two pre-reacted shapes in contact with the appropriate mixture of reactants sandwiched in between, and triggering the reaction. The process is called SHS if the reaction front sweeps the joint, with the reaction having been triggered with the bulk of the reactant below the triggering temperature. It is called CS if all of the reactant is heated above the triggering temperature to cause simultaneous, bulk reaction. Examples of CCCs joined this way include Al_2O_3/TiC, Al_2O_3/SiC, and MgO/SiC. The carbide phase appears as "rivers" in a matrix of the oxide.

In sinter bonding, various ceramic composites can be joined by diffusion, with various amounts of liquid phase being present. Many possibilities exist, including Al_2O_3/SiC, Al_2O_3/Si_3N_4, SiC/PSZ, and sialon/TiN.

With these processes, overall shape complexity and component size are limited, but not as much as for individual molded ceramics.

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[10] The classic "thermite" reaction involves the highly exothermic reaction between Fe_3O_4 and Al—both in a powdered form—to produce Al_2O_3 and molten iron. There is a sister reaction to join copper with CuO_2 and powdered Al.

[11] The concepts of "direct bonding" and "indirect bonding" were described in Chapter 12, Subsection 12.1.3.

14.5.4 Welding of CMCs and CCCs

Ceramic–ceramic composites should be able to be welded to produce good joint integrity and excellent temperature serviceability using non-fusion diffusion welding, various friction welding processes, or certain fusion welding processes, such as LBW and EBW, with their virtually unlimited melting capability. The diffusion welding process will closely resemble the direct bonding process of sinter bonding, although it may be practiced after initial sinter densification, relying on grain growth to help effect the bond. In fusion welding, the integrity of the reinforcing phase might be lost, depending on its nature and form. Metal-reinforced ceramics can also be welded by solid-state diffusion welding, usually with the aid of a metallic intermediate layer.

Specific methods for welding monolithic ceramics are covered in Chapter 12, Section 12.5.

14.5.5 Brazing of CMCs and CCCs

Ceramic-matrix composites (CMCs) can be joined to one another, to a monolithic ceramic or metal, or to a ceramic-ceramic composite (CCC) using brazing. For ceramic-ceramic types, ceramic fillers would almost certainly be preferred. For metal-reinforced ceramics, metal braze fillers would likely be preferred, but ceramic fillers are also possible. The general methods for brazing monolithic ceramics described in Chapter 12, Section 12.4, apply for these ceramic-based composites. Naturally, with brazing, joint design is important to offset the loss of continuity of reinforcement across the joint.

Table 14.9 lists some important brazing processes and fillers used for joining ceramic-matrix composites (CMCs) as well as carbon–carbon composites (CCCs).

14.5.6 Bonding CMCs and CCCs with Adhesives or Cements and Mortars

Like monolithic ceramics, CMCs and CCCs can be bonded to other CMCs or CCCs or to a monolithic ceramic or metal using properly selected organic, polymeric adhesives for non-thermal applications, and using inorganic adhesives (i.e., cements and mortars) for elevated-temperature applications. Specific methods are described in Chapter 12, Subsection 12.3.2.

14.6 JOINING CARBON, GRAPHITE, OR CARBON–CARBON COMPOSITES (CCCs)

14.6.1 Description of Carbonaceous Materials

Carbon, graphite, and carbon-matrix or carbon–carbon composites, which can be generically referred to as "carbonaceous materials," vary widely in their degree of

Table 14.9 List of Brazing Processes and Fillers for Ceramic-Matrix Composites (CMCs) and Carbon–Carbon Composites (CCCs)

Preferred Brazing Processes for CMCs (and Monolithic Ceramics)
- Torch brazing
- Induction brazing (usually in an inert atmosphere for carbides)
- Furnace brazing in an inert (Ar or He) atmosphere (for carbides and some non-oxides)
- Furnace brazing (for most oxide ceramics)

Preferred Brazing Fillers for CMCs (and Monolithic Ceramics)

For carbide types:
- BAg-1 through BAg-7, especially BAg-3 and BAg-4
- RBCuZn–D and BCu
- 85Cu–15Mn
- 85Ag–15Mn

For most oxide and non-oxide types:
- Active Ti–Zr–Be commercial brazes (e.g., 48Ti–48Zr–4Be)
- Experimental Ti–V–Zr, Zr–V–Nb, Ti–V–Be, Ti–V–Cr
- 49Ti–49Cu–2Be
- 85Ag–15Zr
- Many noble metal based alloys: Cu-Au, Cu-Au-Ni, Au-Sn, Au-Ge Ag-Cu-Zn, Ni, Sn, or Au

For premetallized substrates:
- BCu-1, BAg-8, and BAu-8

Preferred Brazing Processes for CCCs (and Monolithic Carbonaceous Materials)
- Vacuum furnace brazing ($<\sim 0.013$ Pa or 10^{-4} Torr)
- Furnace brazing in an inert (Ar or He) atmosphere
- Diffusion or reaction brazing

Preferred Brazing Fillers for CCCs (and Monolithic Carbonaceous Materials)

- Wetted by Mo, Ti, and Zr; forms carbides with Ti, Zr, Si, Cr, V, Ta
  - Ni–clad Ti
  - 48Ti–48Zr–4Be
  - 47Ti–48Zr–5Nb
  - 43Ti–42Zr–15Ge
  - 54Ti–21V–25Cr
  - 35Au–35Ni–30Mo
  - 70Au–20Ni–10Ta
  - 68.8Ag–26.7Cu–4.5Ti
  - 70Ti–15Cu–15Ni
  - 80Cu–10Ti–10Sn (for DFB)

crystallinity, their degree of orientation of the crystals (for crystalline types), and their size, quantity, and distribution of porosity in their microstructures. They also all contain various impurities, especially, but not only, oxygen and water. These factors are strongly dependent on the starting materials from which the final materials are produced, and on the specific method of processing. The physical and mechanical properties of these products are, in turn, also strongly affected by starting materials and processing.

Carbon, graphite, and carbon–carbon composites[12] offer exceptional elevated temperature strength and toughness when properly protected against oxidation. Carbon, after all, has the highest melting temperature of all materials at 3,550°C (6,420°F). Carbonaceous materials also have the highest specific heat capacity of any known substance, so they resist heating quite well. The coefficient of thermal expansion of crystalline graphite is highly anisotropic, and this property is used to advantage to tailor the CTEs of composites containing graphite. It is for these properties, primarily, that these materials are employed. Some important properties of some common forms of carbonaceous materials are given in Table 14.10, while Table 14.11 lists some important carbon–carbon composites and their properties.

Joining of carbon, graphite, diamond, and carbon–carbon composites is especially challenging, but there are several options, including, in decreasing order of usage (1) mechanical fastening, (2) brazing, (3) integral mechanical interlocking, and (4) "bonding," in a process related to adhesive bonding.

Table 14.10 Important Carbon-Carbon Composites and Their Properties

Material	*Ult. Ten. Strength MPa*	*Comp. Strength MPa*	*Ten. Modulus GPa*	*Comp. Modulus GPa*	*CTE @20°C* $10^{-6}°C^{-1}$	*Density @ 20°C* g/cm^3
PAN-based unidirectional						
Carbonized	850	400	180	–		1.55
Graphitized	–	375	–	–		1.75
PAN-based fabric						
Carbonized	350	160	105	140		1.5
Graphitized	–	–	–	–		1.6
PAN-based 3-D						
Graphitized	300	120	140	140		1.9
Rayon-based fibers						
Carbonized	60–65	180–190	15	30–35		1.4
HTU (high-tensile, untreated surf.)						
Parallel to fibers	600	285	125	10		1.6–1.8
Perpendicular to fibers	–	–	–	–		–
HMS (high-mod., treated surface)						
Parallel to fibers	575	300	220	250		1.6–1.9
Perpendicular to fibers	4	25	–	7.5		–
High Performance						
65 vol.% unidirectional	690	–	185–200	–		1.7
55 vol.% orthogonal	–	–	75–100	–		1.6

[12] As an element, carbon can exist in any of several allotropic forms, including as amorphous carbon (commonly seen in soot, and known as "lamp black"), as crystalline graphite (which has a strong, covalently bonded 2-D network of layers, held together layer-by-layer by weak van der Waal's forces, which lead to the slippery feel of this material), or as three-dimensionally crystalline diamonds (held together by the strongest of all covalent bonds).

Table 14.11 Some Monolithic Carbon Materials and Their Properties (Compared to Some Metals, Ceramics, and Composites)

Material	*Density at 20°C g/cm³*	*Tensile Strength, MPa*	*Comp Strength, MPa*	*Modulus, GPa*	*CTE °C⁻¹(°F⁻¹)*
Diamond	3.5	50,000	–	1,000	1.2(0.55)
Graphite	2.2	2,000	–	260	~1.0(~0.65)
Graphite, pyrolitic	2.2	2,700	–	380	2.7(1.5)
CFRP graphite	1.4–2.2	650	–	70–200	1.0–3.0()
GFRP epoxy	1.8	100–300	–	7–45	–
Wood (// to grain)	0.4+	50–150	25–75	9–16	–
Wood (⊥ to grain)	1.8+	–	–	0.6–1.0	–
Concrete	2.4–2.5	20–65	40–130	45–50	–
Fe	7.87	240	–	200	11.7()
Ni	8.9	345–655	–	180	13.3()
W	19.3	375–400	–	345	4.5()
Ti	4.54	235	–	102	9.2()
Al_2O_3	3.9–4.0	207	2,000–3,000	380	8.8()
ZrO_2 (PSZ)	–	270	1,800–2,600	150	6.5()
SiC	2.2–2.5	180	1,600–3,000	340–470	4.7()
Si_3N_4	3.2	250	3,000–6,000+	305–390	2.1()

Brazing generally offers the best joint strength if the fundamental problem of achieving wetting can be overcome. Carbon and graphite are among the most difficult materials to wet with molten metals, making carbon and graphite vessels ideal choices for containing molten melts during their initial metallurgical production as well as in subsequent processing (e.g., by casting). Mechanical fastening must be done carefully to prevent damage to the inherently soft and sometimes brittle material, and to prevent galvanic corrosion as well as oxidation of the metallic fasteners. Carbon and graphite are extremely cathodic, so they render almost all metals highly anodic, most notably Mg, Al, Zn, steels (Fe–C and Fe–C–X alloys) and Ni alloys. Since graphite and carbon–carbon composites are often used for their refractoriness, metallic fasteners can be subjected to severe oxidation. Nevertheless, except for integral mechanical attachment using interlocking geometric features on the carbonaceous joint elements, mechanical fastening generally offers the highest temperature serviceability. Adhesive bonding using organic/polymeric adhesives also presents challenges for achieving wetting, but it can be done. Obviously, service temperature is severely limited by the organic/polymeric adhesive, unless, as part of the bonding process, the resinous adhesive is intentionally pyrolized, in which case the joint is as refractory as the base material(s). If this is the case, this approach offers the very highest temperature serviceability.

A special challenge in joining the carbonaceous materials to other materials is to match or otherwise deal with the coefficients of thermal expansion. The CTE for these materials ranges from 2×10^{-6} to $8 \times 10^{-6} {}^{\circ}C^{-1}$, but can be negative in some directions

for some anisotropic forms of graphite, and can easily be made to be zero in a properly designed composite.

14.6.2 Joining by Mechanical Fastening and Integral Attachment

Mechanical joining is probably the most common method of joining graphite and carbon–carbon composites, particularly to other materials and especially metals. The ablative tiles used to protect NASA's space shuttles from the severe heating encountered during re-entry to the atmosphere from outer space are mechanically fastened, as well as bonded, to the underlying metallic structure. These tiles are used on the leading edges of wings and other control surfaces and are attached mechanically to allow expansion as well as replacement when needed.

Three problems must be dealt with when employing fasteners to mechanically join carbon, graphite, and carbon–carbon composites to one another or to other materials: (1) physical damage to the inherently soft and brittle carbonaceous substrate caused by fastening loads; (2) thermal stresses from CTE mismatch; and (3) galvanic corrosion or oxidation of the fastener.

Carbonaceous materials can be mechanically joined using interlocking part features, clamps, brackets, or fasteners (usually bolts) or wiring. When bolts are used, clamping loads must be kept to reasonable levels, and stress concentrations must be minimized. Large bearing areas under heads and nuts, often achieved through the use of washers (especially conforming washers) but possibly by integral design features, are used. To minimize thermally induced stresses from the combination of extreme excursions of temperature (often from room temperature, or well below, in outer space, to over 3,000°C (5,400°F)) and/or differential coefficients of thermal expansion, joints are designed to allow slip. Fastener holes are intentionally made loose fitting rather than tight fitting, and slotted rather than round. Clamps and brackets and interlocking features are also designed to allow movement at least in one direction.

To prevent galvanic corrosion and/or high-temperature oxidation, fasteners are usually fabricated from titanium alloys, temperature- and corrosion-resistant Ni- or Co-based superalloys, or graphite or carbon–carbon composites. Oxidation-resistant coatings are also often used.

14.6.3 Joining by Brazing

The two major difficulties to be overcome in brazing carbonaceous materials to themselves or to other materials are achieving wetting and dealing with thermal expansion. So, nothing new!

Wettability

The wetting characteristics of all amorphous carbons, crystalline graphites, and carbon–carbon composites are generally poor, but are strongly influenced by such impurities as oxygen or water that are easily adsorbed onto the surface or absorbed

into the bulk of the material. Moisture absorption always occurs, to some extent, with levels as high as 0.25 wt.%. Brazeability also depends on the size and distribution of pores, which can vary significantly from one grade to another, depending primarily on the manufacturing method employed. Some graphite is so porous that all available filler metal is drawn into it, resulting in filler-starved joints. Other types are so dense and impervious that adhesion of filler by mechanical locking is virtually nonexistent.

In order to promote wetting, surface activity must fundamentally be increased, and problems of impurities and porosity must be dealt with. Specific approaches for doing this can be found in references on brazing carbon and graphite (e.g., Anikin *et al.* (1977), Amato *et al.* (1974)).

Thermal Expansion

A major consideration when brazing carbon, graphite, and carbon–carbon composites is the effect of the coefficient of thermal expansion of these materials. In these materials, CTEs may be less than, equal to, or greater than those of the refractory or reactive metals (e.g., W, Mo, Ta, Nb, Ti, and Zr), but are always less than the common structural metals and alloys (e.g., Fe-, Ni-, and Co-based alloys). In some highly anisotropic forms of graphite or specially designed (CTE-tailored) carbon–carbon composites, the CTE can even be negative in certain directions. Table 14.10 lists the CTEs for various monolithic and composite forms of carbon compared to various other important materials.

The mismatch with metals used as the bases for brazing alloys (e.g., Ti, Zr, Cu, Ag, Au, and Pt) is a particular problem. Joint failure can occur, particularly during thermal cycling (even during the process of brazing), if too great a difference in CTE exists between the carbonaceous material and the brazing filler metal. Differential CTEs can cause problems in getting the molten brazing filler metal to flow in the joint gap if the gap opens up too much or squeezes too far closed.

Brazing to Dissimilar Materials

Brazing carbonaceous materials to dissimilar materials can cause problems because the carbonaceous materials have little or no ductility and can be weak under tensile loading. These adverse conditions are usually compensated for in graphite-to-metal joints by brazing the graphite or carbon–carbon composite to a transition piece of a metal with a CTE near that of the graphite. Examples of suitable metals for such transitions are Mo, Ta, and Zr. The transition piece can be subsequently brazed to a structural metal, if required. This technique minimizes shear cracking in the graphite by transposing the stresses resulting from the large difference in thermal expansion to the metallic components, where they can be accommodated by plastic strain. Thin sections of metals, such as Cu or Ni, that deform easily when stressed have also been successfully used for brazing graphite to dissimilar metals.

Brazing Techniques for Carbonaceous Materials

Graphite and carbon-carbon composites are inherently more difficult to wet with the more common brazing filler alloys. Most merely ball up at the joint, with little or no

wetting action. Two techniques are used to overcome this wetting difficulty. First, the graphite or carbon–carbon composite is coated with a more readily wettable layer, such as a 0.0002–0.006 mm (0.008–0.031 mil) thick layer of Mo or W applied by chemical vapor deposition (CVD). This coated or metallized layer can then be brazed using something like BCu-1. Second, brazing filler metals that contain strong carbide-forming elements, such as Cr, Ti, or Zr, can be employed. Such elements react with the carbon in the substrate to form carbides that give rise to intimate bonding.

Another brazing option, in theory, is to employ exothermic brazing (e.g., by SHS or CS). By using fillers containing materials that react to form carbides with substantial exothermic heat of reaction, joining should be possible.

Brazing Filler Metals for Carbonaceous Materials

Several brazing filler metals have been experimentally developed for brazing carbonaceous materials to themselves or to refractory metals, as described in Chapter 12, Subsection 12.4.3 (active-metal brazes) for brazing to carbonaceous materials, and Chapter 7, Subsection 7.5.4 or Chapter 11, Subsection 11.2.4 for brazing to refractory metals.

While usually not particularly useful for materials inherently suited to high-temperature service, carbonaceous materials, like ceramics and glasses, can be soldered using In-based solders (see Chapter 8, Subsection 8.5.8).

14.6.4 Joining by Adhesive Bonding

Carbonaceous materials can be joined by the use of adhesives. Because carbonaceous materials (e.g., graphite and carbon–carbon composites) are usually chosen for their refractoriness in the first place, and service will inevitably involve extreme temperature exposure, the adhesives that are employed are usually pyrolized to effect the bond. This process changes the organic polymeric resin to a carbonaceous material itself by thermally decomposing the polymer, and effects its adhesion through the formation of covalent bonds *in situ*. Two of the adhesive resins used are furfuryl alcohol and phenolics. These resins are often filled with carbon powder to reduce shrinkage and improve the final bond strength. Several proprietary formulations are available, but all employ the same basic mechanisms.

Carbon and graphite and carbon–carbon composites are prepared for general purpose bonding by (1) abrading the faying surfaces with emery cloth to cause roughening, (2) removing dust, and (3) degreasing with acetone solvent.

14.7 JOINING CEMENT AND CONCRETE

Methods for joining cement and concrete using mechanical means (e.g., fasteners and integral mechanical interlocking features) were described in Chapter 3, and using chemical means (e.g., adhesives) were described in Chapter 12, Subsection 12.3.2, as

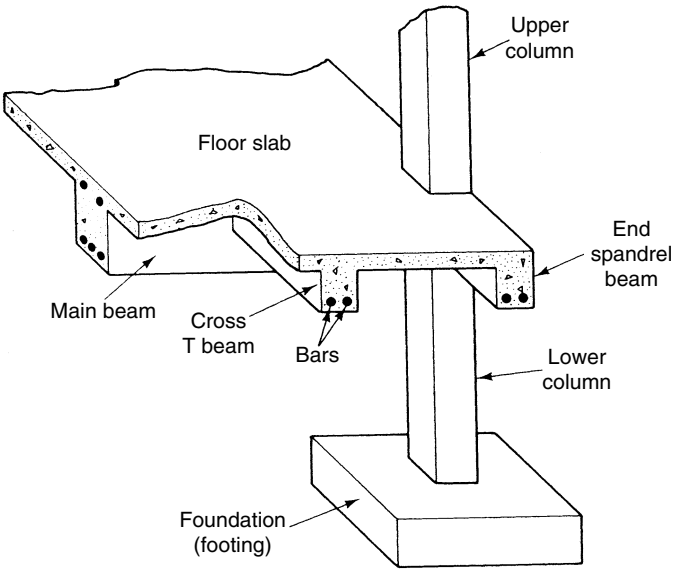

Figure 14.11 Schematic illustration of how reinforced cement and concrete can be joined to the steel or poured concrete structure of a building. (Reprinted from *Reinforced Concrete: A Fundamental Approach*, 5th edition, E.G. Nawy, Figure 4.3, page 74, Prentice Hall, Upper Saddle River, NJ, 2003, with permission of Pearson Education, Inc., Upper Saddle River, NJ.)

these are basically ceramic materials. When cement (or its already-reinforced composite cousin, concrete) is turned into an even more impressive composite through the incorporation of steel-reinforcing bars or meshes, joining to achieve matching properties (particularly strength) across the joint is not particularly difficult. The exposed ends of macroscopic reinforcements are simply welded or, in some cases, mechanically joined by wire wrapping, to achieve continuity of the reinforcement.[13] Figure 14.11 schematically illustrates several approaches.

14.8 JOINING WOOD: A NATURAL COMPOSITE

Wood is a fascinating natural composite material. Forests of the world have provided wood for shelter, fuel, tools, boats and ships, and even machines for thousands of years. Its abundance and the ease with which it can be shaped and joined made it an ideal material for our early ancestors. Besides having impressive structural properties of strength and toughness, and excellent thermal insulating qualities, wood is unique among important engineering materials because it is a renewable resource.

Wood is a living thing—a plant. While the detailed macrostructure and microstructure of wood differ from species to species (e.g., fast-growing softwoods

[13] It is important to note that the surfaces of steel reinforcing bars are embossed with raised circumferential rings, spirals, or crossed spirals to form a diamond pattern. These raised features allow the cement to fully encompass the reinforcing bar and, once set, mechanically lock the bar securely to the cement or concrete.

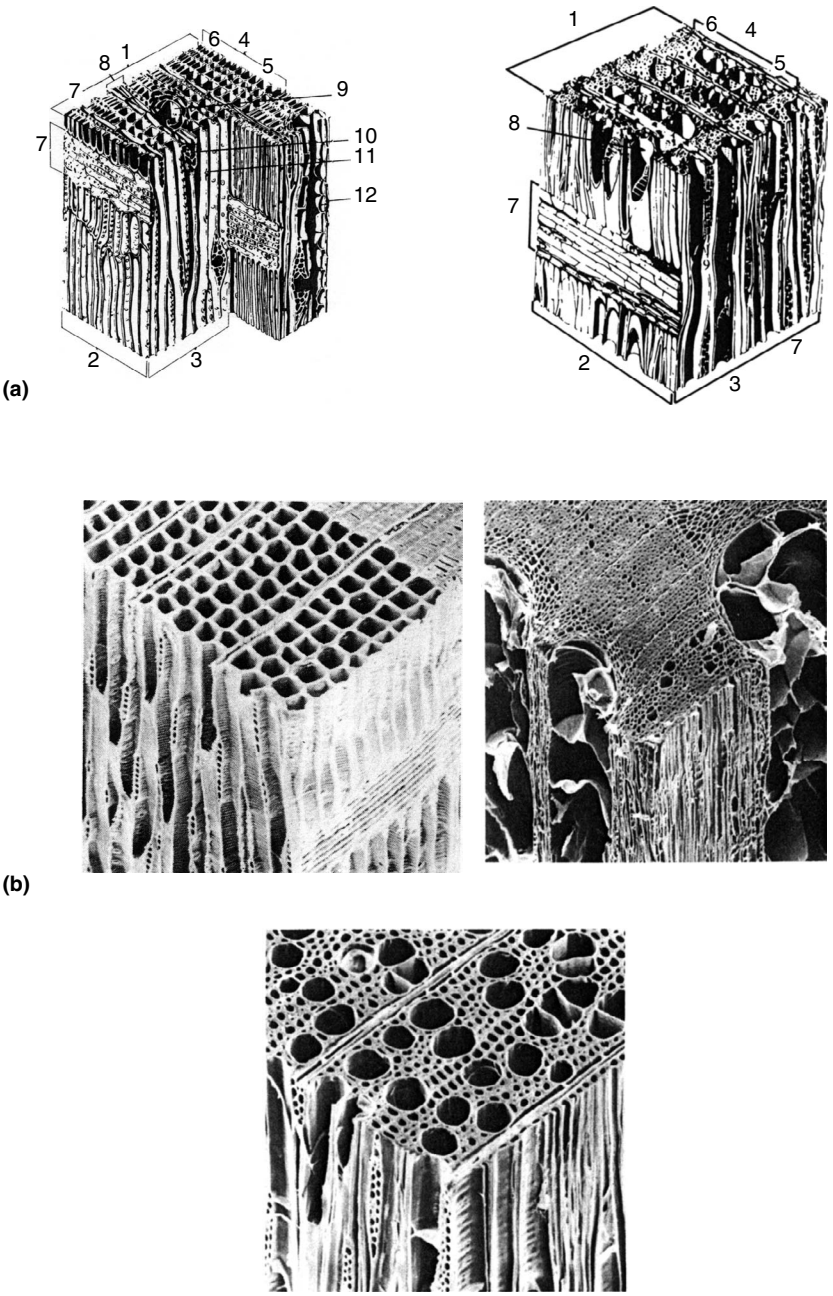

Figure 14.12 Schematics showing the macrostructure of (a) softwood and (b) hardwood. (Reprinted from *Engineering Materials and Their Applications*, 4th edition, Flinn, R.A., and Trojan, P.K., Figs. 17.15 and 17.16, pages 707 and 708, Houghton Mifflin Company, Boston, MA, 1990, with permission.)

like pine to slow-growing hardwoods like oak, and the difference in the more macroscopic ring structures of deciduous and evergreen versus palm trees), the basic biological cells of wood have similar structures; all are composite materials and structures.

Using a typical hardwood as an example, we see that all wood is comprised of cells. In hardwood, as in softwood, the majority of these cells (known as "fibers") have their long dimensions aligned parallel to the longitudinal growth axis of the tree. Details of the cell structures of the wood provide pathways (known as "vessels") for the upward delivery of water and nutriment from the ground, nutriment-distributing resin ducts, and structural elements to give the tree strength to support its weight and resist the loads from wind, floods, etc. These details, and others shown in Figure 14.12 for softwoods and hardwoods, respectively, give the tree its characteristic "ring structure," which allows the progression of growth to be permanently recorded. All of this detailed structure makes wood a very complex composite of different materials and different structural components.

As a material, wood consists of hard, strong, but brittle lignin deposits, strong, tough hemicellulose deposits, and cellulose fibers. It also consists of open, pore-like structures that reduce weight. Wood is composed of 12–28% lignin, an amorphous polymer, and 25–33% hemicellulose, a low molecular weight polymer formed from glucose and other sugars. When the hemicellulose content is high, the lignin content is correspondingly lower. The difference between softwoods and hardwoods is related to the amount of lignin, with hardwoods, surprisingly, containing less lignin than softwoods. The fine-scale cell structure of wood is shown in Figure 14.13. The strength, stiffness, and density properties of wood are diverse among types, and are impressive, as shown in Table 14.12.

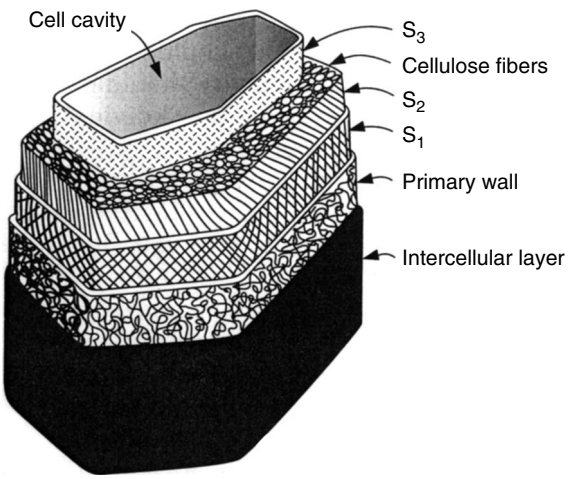

Figure 14.13 Schematic of the fine cell structure of a typical wood. (Reprinted from *Engineering Materials and Their Applications*, 4th edition, Flinn, R.A., and Trojan, P.K., Fig. 17.17, page 709, Houghton Mifflin Company, Boston, MA, 1990, with permission.)

Table 14.12 Typical Mechanical Properties of Woods Grown in the United States

Species	Specific Gravity	Static Bending: Modulus of Rupture, lb/in^{2*}	Static Bending: Modulus of Elasticity, $10^6 lb/in^{2*}$	Compression Parallel to Grain: Maximum Crushing Strength, lb/in^{2*}	Compression Perpendicular to Grain: Fiber Stress at Prop. Limit, lb/in^{2*}	Shear Parallel to Grain: Maximum Shearing Strength, lb/in^{2*}	Side Hardness Load Perpendicular to Grain, lb
Softwoods							
Eastern white pine	0.34 Gr[2]	4,900	0.99	2440	220	680	290
	0.35 kD	8,600	1.24	4800	440	900	380
Douglas fir (Coast)	0.45 Gr	7,700	1.56	3780	380	900	500
	0.48 KD	12,400	1.95	7240	800	1130	710
Western red cedar	0.31 Gr	5,200	0.94	2770	240	770	260
	0.32 KD	7,500	1.11	4560	560	990	350
Redwood (young growth)	0.34 Gr	5,900	0.96	3110	270	890	350
	0.35 KD	7,900	1.10	5220	520	1110	420
Hardwoods							
White ash	0.55 Gr	9,600	1.44	3990	670	1380	960
	0.60 KD	15,400	1.74	7410	1160	1950	1320
Yellow birch	0.55 Gr	8,300	1.50	3380	430	1110	780
	0.62 KD	16,600	2.01	8180	970	1880	1260
Black cherry	0.47 Gr	8,000	1.31	3540	360	1130	660
	0.50 KD	12,300	1.49	7110	690	1700	950
Hickory (pecan)	0.60 Gr	9,800	1.37	3990	780	1480	1310
	0.66 KD	13,700	1.73	7850	1720	2080	1820
Maple (big leaf)	0.44 Gr	7,400	1.10	3240	450	1110	620
	0.48 KD	10,700	1.45	5950	750	1730	850
Oak (white)	0.66 Gr	8,300	1.25	3560	670	1250	1060
	0.68 KD	15,200	1.78	7440	1070	2000	1360

*Multiply by 6.90×10^{-3} to obtain MPa
*Load db_1 to make standard-diameter impression, multiply by 4.44 to obtain Newtons.
†Gr = green state; KD = kiln-dried to 12% moisture
Reprinted from *Engineering Materials and Their Applications,* 4th ed., Flinn, R.A., and Trojan, P.K., pages 707 and 708, Boston, Houghton Mifflin Company, pages 707 and 708, Figs. 17.15 and 17.16, 1990, with permission.

Wood can be joined using mechanical fasteners (e.g., threaded screws and unthreaded nails being most common), integral mechanical interlock design details (e.g., mortis-and-tenon, dovetail-and-groove, etc.), and adhesives. Examples of these types of interlocking features (which are often also used when adhesive bonding is performed) are given in Chapter 3, Subsection 3.5.3, and are shown in Figure 3.43. Examples of preferred adhesives are given in Chapter 5, Subsection 5.4.9.

14.9 ACHIEVING MAXIMUM INTEGRITY IN JOINTS BETWEEN COMPOSITES

As stated at the beginning of this chapter, the challenges posed to joining by reinforced materials or composites come from attempting to match the strength or other functionally specific properties in the resulting joint with those for which the base material was selected in the first place. The degree of success that can be attained depends on the matrix types and reinforcement form, and on the nature of the joining process to be employed.

For polymer-matrix composites, adhesive bonding can come close to matching substrate properties in the actual joint area, in both thermosetting and thermoplastic types. This is often achieved by using laminated splices or doublers, bonded across the joint external to the composite laminate proper, or by using adhesives that are filled with a particulate, chopped fiber, or whisker form of the same reinforcing material used in the composite. In thermoplastic types, welding, using either heat or solvents (in the form of solvent cementing), can usually produce nearly identical properties in the joint and substrate.

For metal-matrix composites, the integrity or continuity of reinforcement is almost never obtained, or it is disrupted across the joint. Again, splice plates or doublers can be used, or, if the form of the reinforcement is discrete particles, short fibers, or whiskers, in either weld or braze fillers could be used. A close match of properties across the joint can be produced by proper joint design and the following welding techniques: solid-phase, non-fusion welding, using resistance spot or seam, capacitor-discharge (percussion), or diffusion welding.

For ceramic-matrix and carbon–carbon composites, there are some good possibilities for achieving close property matching between the joint and the substrate, again provided the reinforcement is not continuous and aligned. In ceramic–ceramic composites, inorganic adhesives or ceramic brazes could be formulated to contain some discrete reinforcement material(s). In carbon–carbon composites, bonding by pyrolizing a carbon-filled resinous adhesive can come close to matching properties across the joint.

With mechanical fastening and integral feature interlocking, the continuity of a continuous adhesive is always lost in all types of composites—polymeric, metallic, and ceramic.

Obviously, any time continuous fiber reinforcements are employed in the composite, matching properties across the joint still proves to be extremely difficult or impossible, given the current level of composite joining technology. At the present time

there is no perfect means of joining composites, any more than there is for joining monolithic materials, although perhaps less so. Repairing steel-reinforced concrete and reattaching limbs clearly exemplify the general approach, but developing new applications from these accomplishments will be extremely difficult. However, there is hope if the concepts of "self-healing materials" coming out of nanotechnology can be expanded upon (Messler, 2003).

SUMMARY

Composites are materials that are actually composed of two or more other materials, one in the form of a property-enhancing *reinforcement* for the other, called a *matrix*. The resulting properties of the combination, or "composite," are superior to or unique from those attainable in any individual so-called "monolithic" material. Composite materials are principally characterized by the material that comprises their matrix, with major types being polymer-matrix (e.g., thermosetting or thermoplastic), metal-matrix, intermetallic-matrix, ceramic-matrix, glass-matrix, or even carbon-matrix composites. The reinforcement in any of these matrices can be metallic, intermetallic, ceramic, glass, polymeric, or carbon-based (i.e., carbonaceous). The form of the reinforcement, which also secondarily characterizes the composite, can be discrete particles (on either a micro- or nano-scale), discontinuous or continuous fibers (either randomly oriented or aligned), random or oriented single-crystal whiskers, or oriented laminates.

The joining of composites poses a special challenge—how to achieve strength or other properties comparable to those of the parent joint elements in and across the joint. This is because it is difficult or impossible to achieve continuity of the reinforcement across the joint. The options for joining composites depend primarily on the matrix but also on the nature of the reinforcement.

Polymer-matrix composites or fiber-reinforced plastics (FRPs) are usually adhesively bonded or mechanically joined by either fasteners or integral mechanical interlocking design features. Thermoplastic types can also be welded or thermally bonded, however. The polymeric adhesive used generally matches the matrix (i.e., thermosetting adhesives for thermosetting polymer-matrix composites, and thermoplastic adhesives for thermoplastic polymer-matrix composites). For joining thermosetting and thermoplastic composite or monolithic materials, adhesive alloys composed of both thermosetting and thermoplastic active agents are used. In mechanical fastening, damage to continuous reinforcements must be avoided if possible during fastener hole preparation. This is usually accomplished by "softening" the region where the hole will be created by eliminating or "dropping-off" reinforcement or by using reinforcement-free inserts. Otherwise, the same general principles used with monolithic polymers apply.

Metal-matrix composites, or MMCs, can be brazed, adhesively bonded using organic/polymeric or inorganic/ceramic or glass adhesives, or welded. In welding and brazing, it is the metallic matrices that are being joined, so the choice of filler (if any) and process must consider compatibility with these matrices. At the same

time, however, damage to the reinforcement (especially continuous fibers) by elevated temperature and localized pressure or deformation must be minimized. Solid-phase, non-fusion welding or resistance- or capacitor-discharge welding (which cause minimal melting) are good choices. The goals are to minimize the peak temperature and time at temperature during heating and to minimize physically damaging reinforcements outright or chemically through reactions between the reinforcement and the metal of the matrix. In mechanical fastening, possible fiber damage must again be considered, and galvanic corrosion must be avoided or guarded against.

Ceramic–matrix composites (CMCs) are usually brazed or adhesively bonded, although ceramic–ceramic composites (CCCs) can be fusion or non-fusion welded. Some CMCs can be diffusion welded like their monolithic counterparts. In brazing, achieving wetting is the major challenge, and the same techniques are used as with monolithic ceramics (i.e., active brazes or metallization of the ceramic substrate, or ceramic brazes). Adhesive bonding usually uses inorganic cements and mortars. Mechanical fastening and integral attachment are generally not used.

Carbon, graphite, and carbon–carbon composites can be mechanically fastened, integrally mechanically interlocked, brazed, or bonded. In brazing, wetting is again a major challenge, but can be achieved by metallizing or by using strong carbide-forming additives in the metal filler alloy. In bonding, a resinous adhesive is pyrolized *in situ* to effect bonding. Resulting properties are excellent.

The joining of concrete (a widely used synthetic composite) and wood (a widely used natural composite) are described elsewhere in this book.

In inherently brittle ceramic- and carbon-matrix composites, matching CTEs are critical for all forms of joining, especially for brazing or cementing.

QUESTIONS AND PROBLEMS

1. Define what is meant by a *composite material.* Differentiate between a ''natural'' and a ''synthetic'' composite; give three examples of each. Why is it appropriate to speak of composites as structures?
2. Describe the role of the matrix in a composite material, citing two generic examples. List the basic materials that can constitute the matrix of a composite material, and give one example of a well-known composite, natural or synthetic, with each type of matrix.
3. Describe the role of the reinforcement in a composite material, citing mechanical, electrical, and thermal examples. List the basic materials that can constitute the reinforcement of a composite material, and give one example of a well-known composite (with any matrix material), natural or synthetic, with each type of reinforcement.
4. What various forms can the reinforcing phase of a composite take? Give a well-known example (with any matrix material) for each form.
5. What are some of the particular advantages of composites versus monolithic materials? Refer to some mechanical, electrical (or magnetic), and thermal examples.

6. In general, what are the special challenges posed by a composite material to joining? Explain how the matrix and the reinforcement influence joining.
7. What are the generic options for joining polymer-matrix composites? Give an example of a situation in which each type of joining process is used.
8. What are the special considerations associated with mechanically fastening polymer-matrix composites with unidirectional, continuous fiber reinforcements? How are these particular problems overcome in practice?
9. How and why is the general approach of employing integral mechanical (interlocking) attachment features appropriate and advantageous to the joining of polymer-matrix composites? Is the approach more appropriate and advantageous to one type of polymer than the other or not, and why?
10. How are polymer-matrix composites joined by adhesives? Differentiate between the adhesive bonding of thermosetting- and thermoplastic-matrix types.
11. How might reinforcement be achieved across an adhesively bonded joint, or can it not be achieved?
12. Explain how "co-curing" can be used to join thermosetting-matrix composites or fiber-reinforced plastics. What is the advantage of co-curing versus more conventional adhesive bonding?
13. Explain why and how thermoplastic-matrix composites can be thermal bonded or welded. How can solvent cementing of such composites be considered welding? Or can it?
14. What are the special properties of metal-matrix composites, or MMCs, that tend to drive joining process selection? What are the options for joining MMCs, assuming service temperature is very important?
15. Describe the special challenges of welding MMCs, and give some examples of specific processes that will produce sound joints in specific MMCs.
16. What are the special problems associated with mechanically fastening metal-matrix composites? How are these problems overcome in practice?
17. What are the special properties of ceramic-matrix composites (CMCs) that tend to drive joining process selection? What are the options for joining CMCs?
18. Explain what is meant by "direct bonding" of CMCs. Give two specific process examples.
19. How can CMCs be joined mechanically using fasteners, special mechanical devices, or integral design features? Give a familiar example application of each.
20. Describe how the brazing of metal- or ceramic-matrix composites differs from the brazing of monolithic metals or ceramics, respectively. How is the brazing of the monolithic and composite forms of metals or ceramics the same, if at all?
21. What are the special properties of carbon, graphite, or carbon–carbon composites that tend to drive the selection of a joining process? What are some of the particular challenges of joining these carbonaceous materials? Give an example of where monolithic carbon or graphite and where carbon–carbon composite is used.
22. Describe the problems associated with mechanically fastening carbonaceous materials, giving at least three specific examples.

23. Describe the problems associated with brazing carbonaceous materials, and give an example of a preferred brazing process and a preferred filler.
24. Explain how the adhesive bonding or simply bonding of carbonaceous materials like graphite or carbon–carbon composites is different from conventional adhesive bonding.
25. Describe how the use of mechanical fasteners, integral mechanical interlocking features, and adhesive bonding can be used to join wood.

Bonus Problems

A. How does the form of a particular reinforcement in a particular matrix affect the mechanical properties? Give an example of at least one mechanical property and provide data to show how form affects this property. What effect does the form have on electrical properties? Give an example.
B. Knowing that most living tissues are actually composites, explain what the matrix and reinforcing phase (or component) are for three examples: one hard, non-vasculated; one semi-hard or soft, non-vasculated; and one soft and vasculated. How would you propose to join each type?
C. Identify at least two examples of a glass-matrix composite; describe the matrix and the reinforcement material and type.
D. Provide an analysis to show how the transfer of load from a fastener to a joint element made from a reinforced composite such as unidirectionally, continuous glass fiber-reinforced epoxy is different from that for a monolithic, isotropic material like epoxy.

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Chapter 15

Joining Dissimilar Material Combinations

15.1 INTRODUCTION

15.1.1 The Need for Joining Dissimilar Materials

As described in the introductory chapter of this book, one of the major reasons or needs for joining is to permit dissimilar materials to be used in a complex structure or assembly, creating so-called "hybrid structures" (i.e., structures that, as a result of being composed of more than one material, offer properties, performance, or other attributes not attainable in any individual material). "Dissimilar materials," as used here, refers to materials of different fundamental types (e.g., metals, ceramics, glasses, polymers, or composites), as opposed to materials with simply different compositions within a particular type (e.g., Al–Mg–Zn versus Ti–Al–V alloys, alumina versus magnesia, polystyrene versus polyurethane). Dissimilar materials enable the achievement of function where design requirements call for diverse and, often, divergent properties, manufacturability, or aesthetics unobtainable in single materials.

Dissimilar materials often enable the attainment of high structural efficiency in several ways. They do this first by minimizing weight by using the lowest density material with the appropriate strength (i.e., highest specific strength) for strength-critical designs, or modulus or stiffness (i.e., highest specific modulus or stiffness) for stiffness-critical designs, or other properties critical to a design, in each area of the assembly or structure. Dissimilar materials also might provide damage tolerance to the overall structure by changing the material and elastic properties along a potential crack path. This imparts damage tolerance to the structure without having to rely on the use of discrete parts that are simply mechanically fastened or attached together. Dissimilar materials can also optimize a design by matching the correct material to the needed property or behavior (e.g., refractoriness, electrical conductivity, thermal or electrical insulation, or corrosion or wear resistance), rather than compromising some areas of the design (or structure) by settling for a less-than-optimal material to fabricate the entire structure. In addition to these important property advantages, the use of dissimilar materials often allows the costs of raw materials and/or fabrication and/or operation in service to be minimized by allowing optimal materials to be used in

specific areas of the design. In this way, inherently expensive or difficult-to-fabricate (and, thus, expensive to fabricate) high-performance materials only need to be used where they are absolutely required and provide real benefit.

For medical purposes, increasingly sophisticated implants (e.g., artificial hip joints, knee joints, elbow joints, heart valves, etc.) demand that very dissimilar materials be joined (e.g., living tissue having to be joined to nonliving materials). This is surely the most demanding challenge that has faced and will likely increasingly face joining specialists (e.g., tissue engineers). Joining of living tissue is discussed in Chapter 16.

Designers are using more and more combinations of materials in their designs due to the availability of more basic types (e.g., advanced metals and alloys; structural, electronic, magnetic, and optical ceramics; specialty glasses; intermetallic compounds and long-range ordered alloys; structural polymers; and synthetic composites), and more varieties within a type (e.g., thermosetting or thermoplastic polymers; polymer-, metal-, ceramic-, intermetallic-, and carbon-matrix composites). The increased and often simultaneous demands for higher quality, better performance, longer life, higher reliability, and lower cost are causing the joining of dissimilar materials to become increasingly important.

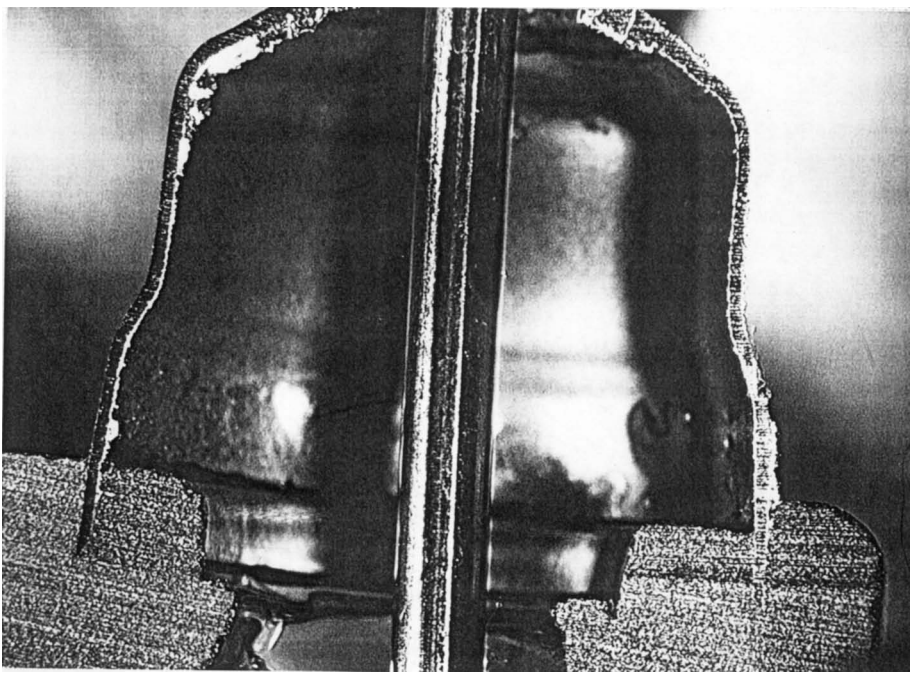

Figure 15.1 Various metal-to-glass joints are used in the manufacture of incandescent electric lightbulbs. In this close-up photograph of a cross-section, a so-called ''housekeeper'' glass-to-metal seal has been made in the parabolic reflector lightbulb. The Ni-plated iron ferrule is sealed to borosilicate (Pyrex) glass. Electrical connection is made by brazing to the iron ferrule. (Courtesy of GE Lighting, The General Electric Company, Cleveland, OH, with permission.)

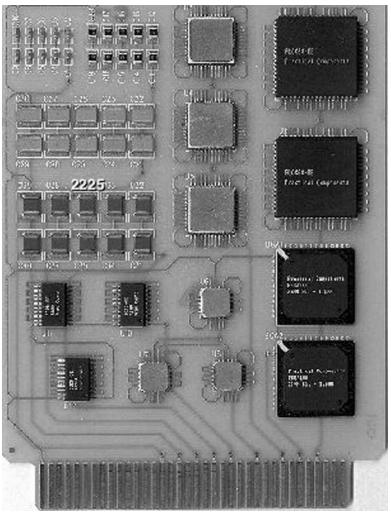

Figure 15.2 Metallized "printed" circuits are joined to a glass-reinforced thermosetting polymer board for support in the microelectronics industry. (Courtesy of Sandia National Laboratories, Albuquerque, NM, with permission.)

Figures 15.1 and 15.2 show two common and important examples where dissimilar materials are joined. In Figure 15.1, glass components of incandescent electric lightbulbs are joined to metal components to provide needed electrical insulation and hermetic sealing, while in Figure 15.2 metallized layers are caused to adhere (i.e., join) to glass-reinforced thermosetting polymer circuit boards to provide the needed electrical circuit on a strong insulated support structure.

15.1.2 The Special Challenges of Joining Dissimilar Materials

The fundamental challenge of joining dissimilar materials is compatibility—actually, incompatibility! In order to produce an acceptable joint in terms of structural strength, structural integrity (i.e., quality and reliability), and structural efficiency, the different chemical, physical, and mechanical properties of the various materials being joined must be, or must be made to appear, compatible. A similar need for compatibility exists for other functionally specific properties being sought in the joined entity (e.g., electrical conductivity in the form of electrical connectivity). Put another way, differences must be minimized, inherently through the choice of materials or through some other means. This becomes increasingly difficult as the basic nature—atomic-level structure, microstructure, properties, and, in some materials (like composites or living tissue), macrostructure—of the various materials involved becomes more different.

Joining a crystalline ceramic to an amorphous glass, which represents a case involving two different types of materials, is relatively simple, just as joining a thermoplastic polymer to a thermosetting-matrix composite is relatively simple. In both cases, there is chemical compatibility (i.e., bonding is either the same or similar enough) and

physical properties (e.g., melting or glass-transition temperatures, coefficients of thermal expansion, or CTEs, or electrochemical activity) are close. On the other hand, mechanical properties can be quite different, as is almost inevitably the case in the relative stiffnesses of a monolithic thermoplastic versus a reinforced thermosetting-matrix composite. On the other hand, in joining a metal to a glass or a metal to a ceramic, the fundamental structures and properties are much different, so joining becomes much more difficult. The problems are most severe when the joining is to be most intimate (i.e., when there is to be actual physical or material continuity from one material or joint element to another).

The compatibility of chemical, physical, and mechanical properties is important during the actual process of attempting to create the joint as well as during the operation of the joint in service. If chemical incompatibilities are great enough, it is usually impossible to produce joints by fusion welding, since the desired intermixing of the materials on an atomic level either will not occur as it should or will occur but result in some kind of degradation in the mixed materials (e.g., embrittlement and cracking). If joining processes are used that do not require such intimacy or extent of intermixing (such as brazing or soldering, some adhesive bonding, or mechanical fastening or integral attachment), joining may be accomplished but adverse chemical reactions might occur over time. For brazed or soldered joints, brittle intermetallic compounds may occur as diffusion progresses, especially in certain environments (e.g., prolonged exposure to elevated temperature). For mechanically fastened or integrally attached joints, galvanic corrosion might occur with time, especially in certain environments (e.g., in the presence of water serving as an electrolyte). For adhesive bonding, as long as the adhesive keeps the incompatible materials from intimate contact with one another, and provided the adhesive is compatible with each and every material involved in the joint, everything should be fine. If physical properties are drastically different, the same thing applies. It may be impossible to produce a satisfactory, crack-free joint by fusion welding, brazing, or soldering if CTEs are drastically different. If the differences are less drastic, such problems as distortion or cracking might not occur during actual joining but might occur with time in service, regardless of the process used to make the joint; the most likely mechanism is thermomechanical fatigue. Even mechanical properties can be incompatible, but because this is less common, it is less often perceived as the cause of an eventual problem (e.g., joint failure). Drastic differences in strength, ductility, or toughness could, for example, cause the joint to be of limited utility or could cause the joined system to be used for what is really only an available property of one of the joint elements.

Achieving successful joints between dissimilar materials requires a sound understanding of the inherent nature of the materials to be joined and of the various joining options and their means of achieving bonding. In Chapters 2 through 10, the various joining options were described. In Chapters 11 through 14, the basic material types were described in terms of how they can be joined to themselves. Now we need to look at combining different materials into sound structural or otherwise functional assemblies using any or all of the joining options at our command. Section 16.4, "Joining of Structures," discusses living tissue and its joining to other living tissue or to non-living materials, as living tissue is as much or more complex and sophisticated a structure as it is a material or even a composite material.

15.2 LOGICAL AND ILLOGICAL COMBINATIONS OF MATERIALS

While every combination of metals, intermetallics, ceramics, glasses, polymers, and composites is conceivable in joined assemblies, some combinations are logical and some are, for the most part, illogical in terms of their compatibility or incompatibility. The more fundamentally dissimilar two materials are, the more one must question the logic of their being combined. Of course, whether a combination ultimately makes sense depends on the application (i.e., the ultimate joining demands). Some combinations may not make sense for use in primary structural applications but may be acceptable for secondary structural[1] applications or for non-structural applications.

Polymers and metals are fundamentally different in strength, elasticity, plasticity, stiffness, melting temperature, service temperature, electrical and thermal characteristics, chemical stability and durability, etc. Polymers might logically be joined to metals, however, where there is a need to (1) provide corrosion protection of a surface; (2) reduce friction at a surface; (3) enhance damage tolerance by arresting crack propagation in one material or the other; (4) provide vibration damping or noise deadening; or (5) reduce weight (in less severely loaded areas of a structure). On the other hand, if the metal was also being used for its resistance to elevated or cryogenic temperature, then joining to a polymer would not be logical as the polymer would not perform in this environment. Likewise, joining a ceramic to a polymer is generally illogical since the ceramic is almost always being used for its corrosion and wear resistance and its refractory properties. But there are exceptions, such as when a ceramic is added to a polymer to enhance strength, hardness, or stiffness.

Just as some combinations of materials might generally be considered illogical because of the drastically different structure and properties of each, it is usually very difficult to join such significantly different materials. Furthermore, the options for producing sound joints become more limited. Table 15.1 summarizes the logical and illogical combinations of materials in joints for various principal service conditions and also quantifies the difficulty that can be expected in creating a suitable joint. Preferred joining options, in decreasing order, are also listed. This tabulation is by no means purported to be precise, but it can serve as a useful guide. The hybrid processes of rivet-bonding, weld-bonding, and weld-brazing would be practical or possible only if their fundamental parent processes were possible.

In the sections that follow, methods for joining various material combinations will be described by generic combination.

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[1] As used here, and as typically used, "primary structural applications" are those where the successful performance of the material(s)—and in this case, the joint(s)—is (are) essential or critical to the performance of the structure. Loads are usually high, and the principal load path runs through the material elements. Failure of a primary structural element or area will result in the complete and often immediate loss of the system. "Secondary structural applications" are those where failure of this structural element or area will not result in the complete and immediate failure or loss of the system.

Table 15.1 Summary of Logical Combinations for Materials in Joints: Relative Difficulty of Joining and Joining Options (in descending order of preference)

		Material 1 Difficulty[a]	*Material 2 Options*[b]
Metal A	Metal A	1	M, A, F or N, B, S
	Metal B	1–5	A, B, S, M[c], F[c], N
	Metal A–matrix composite	2–3	B, N, F, M, A
	Metal B–matrix composite	3–4	B, N, F, A, F[c]
	Ceramic	3–5	B, A, M, S
	Ceramic–matrix composite	3–5	B, A, M
	Glass	3–4	S, M
	Intermetallic compound	3–5	B, M, N, F[d]
	Thermoplastic polymer	1–3	A, M
	Thermosetting polymer	1–3	A, M
	Polymer–matrix composite	2–3	A, M
Ceramic A	Ceramic A	1–3	A, M, N, F, B
	Ceramic B	2–4	A, M, B, N, F[c]
	Ceramic A–matrix composite	1–3	B, M, A, N, F[c]
	Ceramic B–matrix composite	2–4	B, M, A, N
	Glass	2–4	F, N, A
	Metal-matrix composite	3–5	B, M, N
	Intermetallic compound	3–5	B, M, F[c]
	Polymer	2	A
Polymer A	Polymer A	1–2	A, F/N, M
	Polymer B[e]	1–2	A, F/N, M
	Polymer C[f]	2–4	A, M, N
	Polymer A-matrix composite	1–2	A, M, F/N
	Polymer B[e]-matrix composite	1–3	A, M, F/N
	Polymer C[f]-matrix composite	2–4	A, M, N
	Metal or Metal-matrix composite	2	A, M
	Ceramic or Ceramic-matrix composite	2	A, M

[a]Ranked as 1=No problem, 3=Moderate difficulty, 5=Extremely difficult to impossible
[b]A=Adhesive bonding, B=Brazing, F=Fusion welding, M=Mechanical fastening or integral attachment, N=Non-fusion welding, S=Soldering
[c]Depending on compatibility
[d]Like composition thermoplastics or thermosets
[e]A combination of different thermoplastics
[f]A thermosetting to thermoplastic combination

15.3 JOINING METALS TO CERAMICS

15.3.1 General Comments on the Challenges of this Combination

Ceramics are becoming increasingly important as engineering materials. They have long been valued for their refractoriness, hardness and wear resistance, often for their thermal and/or electrical insulating qualities, resistance to corrosion and oxidation,

and (at least for the common masonry cements and concretes), strength in compression. They are becoming increasingly valued for their often unique electrical and magnetic properties (e.g., ferrites), optical properties (e.g., sapphire-alumina), and physical properties (e.g., piezoelectric behavior of, say, titanates). Even the strength and toughness of so-called "advanced structural ceramics" are improving due to one or more of (1) improved processing (including initial refinement or synthesis methods); (2) new methods for toughening (e.g., stabilizing phases, as in partially stabilized zirconia, or controlled micro-cracking or micro-porosity); and (3) new levels of performance made possible by the development of nanocrystallinity. Ceramics are therefore being considered for wider and more demanding applications, and it is frequently desirable to combine the properties of a ceramic with a metal in a structure. Thus, joining of these fundamentally dissimilar materials is becoming necessary, not simply interesting.

In general, ceramics are stronger (especially, but not only, in compression), more tolerant of elevated temperature (for strength and hardness retention and resisting oxidation), less reactive (for resisting corrosion or oxidation), and less thermally expansive or conductive than metals. Some of these differences are shown in Table 12.1. Obviously, there are some exceptions to these generalities, such as the high thermal conductivity of BeO or AlN or the refractoriness of Mo, Ta, and W, but for the most part, they apply.

These differences in properties arise from fundamental differences in atomic structure and microstructure. On the atomic scale, ceramics are bonded ionically or covalently, or by mixed ionic–covalent bonds, while metals are bonded metallically. These different bond types give rise to different cohesive strengths, melting points, and moduli (all higher for the inherently higher strength ionic and covalent bonds than for metallic bonds); differences in plasticity or ductility (due to the ability of metals to slip without disrupting atomic-level periodicity and charge balance and bringing like-charged ions together); and differences in electrical, thermal, optical, and magnetic properties (due to differences in electron distributions and spins). On a microstructural level, ceramics contain inherent microflaws in the form of microcracks and pores, both of which limit strength in tension (which tends to open and extend these flaws) compared to strength in compression. The bonding of ceramics tends to cause them to have larger, more complex dislocations, which make plastic deformation difficult and usually lead to low toughness (i.e., ability to absorb energy without fracturing). All of these factors mean that each material can meet different demands. Such differences in properties and structure (arising from chemistry), however, can make joining difficult or impossible.

It should be pointed out that ceramics (or glasses) and metals are useful when combined to produce joints for structural applications where strength and/or vacuum tightness (hermeticity) are often the primary requirements. They may also be considered simply to form a non-structural ceramic-to-metal interface for electrical and electronic components, or for chemical catalysis or corrosion resistance. In many structural applications, specific characteristics of ceramics have led to their selection for critical components, forming parts of a system that is largely metallic. Here the success of the system depends on the ability to form ceramic-to-metal joints of adequate quality and integrity.

As pointed out in Chapter 1, there are many reasons for wishing to join particular ceramic and metal components (e.g., wear-resistant coatings, thermal oxidation and/or diffusion barriers, thermal or electrical insulation, and others). One's motives can usually be related to design, manufacturing, or economic factors. In an automobile spark plug, for example, an insulating ceramic must be bonded to a conductive metal electrode for the spark plug to function. Metal might be needed to structurally support a ceramic and provide a degree of toughness by serving to arrest any cracks propagating in the ceramic. Or a ceramic might provide a sink for heat dissipation, as in a ceramic-tipped cutting tool. In the moving parts of advanced heat engines, including internal combustion engines and gas turbines, metal may be used instead of ceramics to reduce cost whenever the ceramics are no longer needed for their principal properties (e.g., refractoriness, wear resistance and low density, and, hence, inertia).

15.3.2 General Methods for Joining Metals to Ceramics

Macroscopic[2] metal–ceramic components can be joined by one of three techniques: (1) mechanical joining by interlocking with fasteners or, alternatively, using integral design attachment features; (2) direct joining by non-fusion or fusion welding; and (3) indirect bonding by organic or inorganic adhesives or cements, brazing alloys, or solders. Whatever the process (aside from mechanical joining), the formation of successful joints depends on (1) the achievement of intimate contact between the joint elements; (2) the conversion of these contacting surfaces into an atomically bonded interface; and (3) the ability of the interface to accommodate thermal expansion mismatch stresses generated during cooling after fabrication or temperature changes in service.

15.3.3 Mechanical Methods for Joining

The mechanical fastening or integral attachment of ceramics to metals has been important in traditional applications and is still important in certain new applications. Traditional applications include the "tying-in" or attachment of furnace wall or roof refractory ceramic bricks or tiles with metal hooks, hangers, brackets, or interlocking "dog-bones" (see Figures 12.2 and 12.5). A similar approach is employed in heavy construction of buildings, for example, when metal reinforcing bars (often bent to form a loop that has both ends embedded in one cement or concrete element) are employed. Sometimes threaded studs extend from the cement or concrete to allow the connection of another structural element, often one constructed from metal (e.g., a door or

[2] Bonding on the microscopic scale is an issue in ceramic-reinforced metal-matrix composites or metal-reinforced ceramic-matrix composites for achieving effective load transfer between the reinforcements and the matrix. Bonding at this level will not be considered here; only bonding on a larger, macroscopic scale will be considered.

window frame). A newer application is the mechanical clamping once used more than modern adhesives to attach heat-resistant ceramic thermal protection tiles to the leading edges of NASA's space shuttles' noses, wings, rear fins, and tails.

Attachment by more conventional fasteners, such as specially designed screws or bolts intended for use with cement or mortar (i.e., masonry fasteners), is less popular, but possible. To avoid damage to the brittle ceramic from localized stress concentrations from bearing or clamping loads, bearing and clamping areas must be large. Oversized heads and/or faces on bolts or nuts or washers, not to mention much coarser threads, are typically used. Another means of overcoming localized points of high stress during mechanical joining is to use a compliant metal interlayer between the metal and the ceramic parts. One example is the use of a platinum intermediate layer between a nickel-base superalloy turbine disk and an Si_3N_4 blade; another is the use of lead (Pb) sleeves or anchors to lock threaded fasteners (e.g., bolts) into a holes in a ceramic (e.g., concrete), or to protect the concrete from the concentrated force and/or stress of the metal fasteners.

Fastener holes in ceramics can be difficult to produce unless they are molded and, possibly, fired in. Inherently hard, abrasion-resistant ceramics will cause excessive cutting-tool wear and will often suffer damage themselves by chipping or fracturing. Again, to avoid localized bearing, holes are often lined with metal sleeves or inserts, especially when screws or lag bolts are used.

Mechanical joining provides fairly good mechanical integrity under moderate loads, and thermal expansion differences are relatively easy to accommodate by design (e.g., using expansion joints). The single greatest advantage of mechanical joining, here as anywhere, is that intentional disassembly can be accomplished, thereby facilitating maintenance, repair, upgrade, expansion, or other changes.

Obviously, geometric features that have been designed and fabricated into a ceramic can be used to mechanically attach those components to other components with mating geometric features. Figure 12.6 in Chapter 12 shows an excellent example.

15.3.4 Direct Joining by Welding

In a process of "direct joining" or "direct bonding," one material is joined to another to result in actual primary bond formation of the same type as found in the materials involved, without the need for any intermediate material. Metals and ceramics can be directly joined or bonded to one another by using welding; solid-phase, non-fusion welding is the preferred technique. While fusion welding can be used to join some metals to some ceramics, this is generally far more difficult and rare because some intermixing of the liquid phases of the ceramic and the metal is almost inevitable. It is difficult to see how such fundamentally different materials—even in the liquid state—can intermix on an intimate (i.e., atomic) level. Diffusion bonding is usually the solid-phase welding process of choice, with friction welding being a close second. Far more exotic solid-phase deposition processes such as chemical vapor deposition (CVD) and physical vapor deposition (PVD) are also possible. These latter two processes are not even generally recognized by most people, or even some experts, as welding processes. In fact, they *are*

welding processes by the strict definition of welding (i.e., the formation of a joint between two materials by establishing primary chemical bonds using some combination of heat and pressure (Messler, 1999). What makes these processes different from virtually all other welding processes is that bond formation, and thus joining of one material to the other, is accomplished atom by atom, not en masse. Fusion welding has been successful using high energy density processes like electron beam and laser beam welding.

Diffusion Welding

The success of solid-phase diffusion welding, transient liquid-phase[3] bonding or brazing, or solid-phase welding by hot pressing or pressing and sintering at elevated temperatures (i.e., solid-phase or transient liquid-phase sinter bonding[4]) depends critically on the achievement of adequate intimate (i.e., atomic-level) interface contact. This contact is achieved by pressing together very flat or contour-matching surfaces and relying on the intimate contact obtained between dramatically increased numbers of microscopic asperities to serve as paths for diffusion. Initially, contact is increased by plastic deformation of the metallic joint element. But it is subsequently increased by creep, grain growth, and diffusion in the metal, and, to a lesser extent, in the ceramic components, which will spheroidize and seal any residual porosity. Figures 15.3 and 15.4 schematically illustrate the steps (or stages) involved in liquid-phase bonding and solid-phase bonding, respectively, of metals to ceramics.

In diffusion welding (as opposed to fusion welding), a similar refractoriness (i.e., melting point or range) of the ceramic and the metal is neither necessary nor usual. There are reports of successful welds between such metals as Ag, Al, Au, Cr, Cu, Fe, Nb, Ni, Pb, Pd, Pt, and Zn to alumina (Al_2O_3). One practical example is the diffusion welding of Nb to alumina sapphire at 1,700°C (3,092°F) required in high-pressure sodium vapor lamps used in street lighting. Although diffusion does take time, bonding can occur surprisingly quickly, sometimes in seconds but usually in several minutes or hours.

The direct solid-state bonding of both noble and transition metals[5] to ceramics without the use of any intermediate material or interlayer is believed to be due to some combination of surface and bulk chemical reactions. Usually, the joint is heated (while held together under pressure) to near the melting point of the metal. The metal is usually in a sheet or foil form. For non-oxygen-active metals (e.g., the noble metals, Au, Ag, Pt, Pd, etc.), strong bonds have been produced at pressures around 1 MPa (about 150 psi). For oxygen-active metals, higher pressures of 10 MPa (about 1,500 psi) are generally required. Joint shear strengths can be quite high, up to 8–10 kg/mm^2 (10–15 ksi).

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[3] As used here in "transient liquid-phase diffusion bonding" and "transient liquid-phase sinter bonding," the transient liquid is formed as the result of the atomic-level intermixing, by interdiffusion, of components in the two (or more) solid-state joint elements that react to form a eutectic with a melting point lower than the holding temperature. This is different from using a low-melting intermediate that is added to the joint to melt and, thereby, effect bonding by facilitating diffusion or leading to a reaction with the substrates. This latter situation is really "indirect joining," since an actual intermediate material is needed and employed.

[4] In fact, solid-phase sinter bonding *is* solid-phase diffusion welding.

[5] *Transition metals* are those found near the center of the periodic table and include elements like Fe, Ni, Co, and many others. What makes them transition elements is the way in which they fill sub-levels in their electron shells.

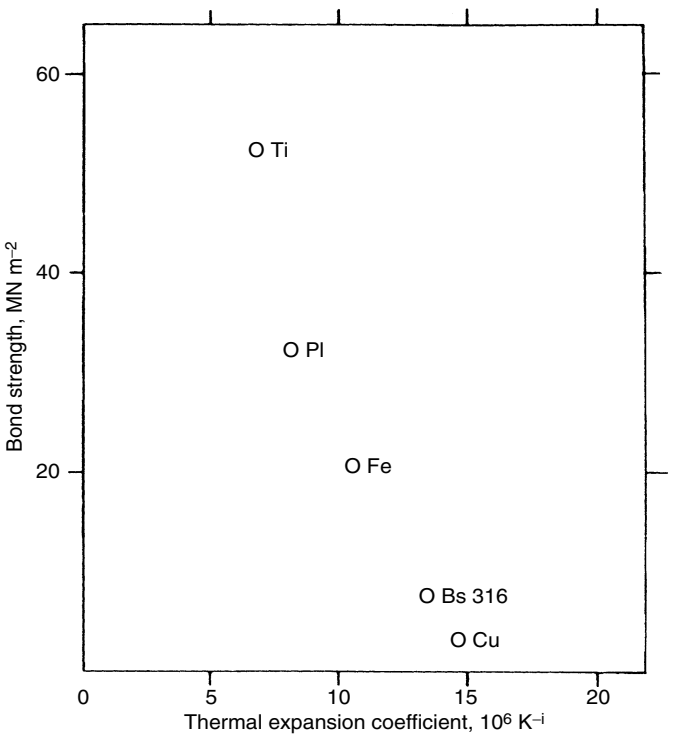

Figure 15.3 A plot of diffusion bond strength versus CTE for various metal-alumina combinations. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 15.1, page 516, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

Figure 15.5 shows a plot of the strength of a diffusion bond between various metal-to-alumina combinations as a function of the CTE for the metal.

Diffusion welding can also be accomplished using a "graded powder bonding technique" to produce a "functional gradient material" (FGM) joint. In FGM joints, the metal-to-ceramic bond is formed by pressing layers of metal and ceramic powders together. A schematic illustration of an FGM joint is shown in Figure 15.6. By grading the composition of the powder layers from pure metal on the metal side of the joint to pure ceramic on the ceramic side of the joint, through intermediate blended or composite compositions, chemical compatibility as well as physical property matching is achieved. This technique is analogous to the graded seal or matched seal commonly employed in metal-to-glass sealing (see Subsection 15.4.4).

Achievement of the necessary contact and bonding for a particular application depends on the judicious selection of not only the materials but also the bonding parameters, such as surface roughness, surface cleanliness or preconditioning, processing environment, pressure, time, and temperature. Some roughening of the metal surface is highly beneficial to facilitate localized plastic deformation, but care must be exercised to maintain macroscopic contour and freedom from contaminants. Increasing

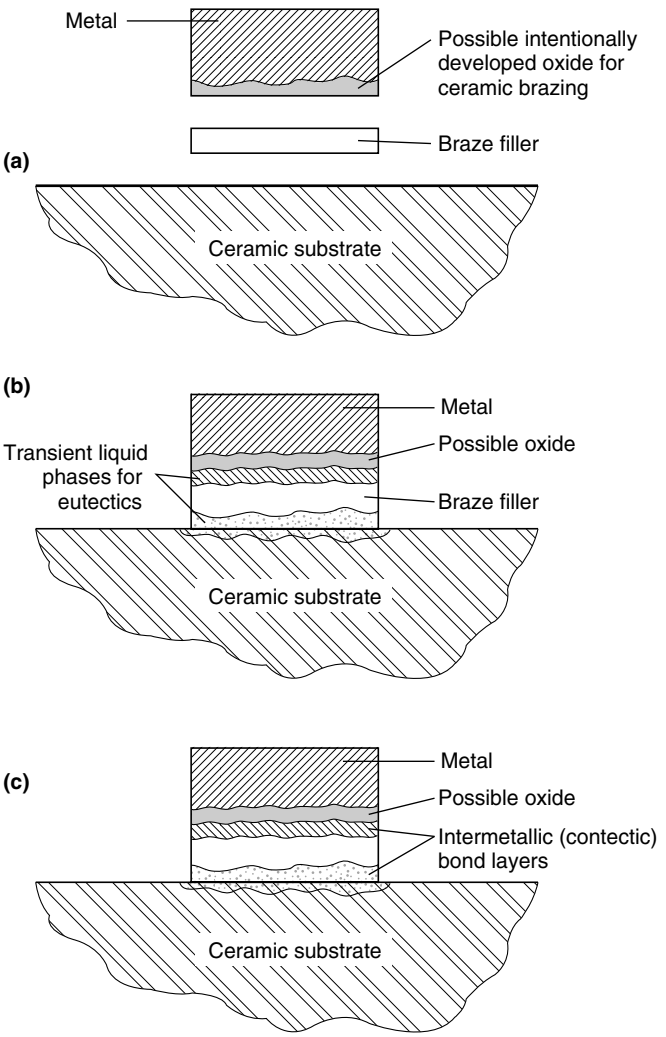

Figure 15.4 Schematic illustration of the stages of liquid-phase bonding of metals to ceramics.

the bonding pressure or time improves contact and bond quality, but not nearly as much as increasing the temperature (due to the Arrhenius relationship between diffusion rate and temperature[6]). Prolonged times or higher temperatures can lead to chemical reactions at the ceramic–metal interface that initially enhance bonding but often progress to cause degradation, as the progressive growth of the reaction zone can generate mismatch strains and stresses from a reaction product with a different specific

[6] The Arrhenius relationship between the rate of diffusion, D, and the absolute temperature, T, is given by $D = \exp^{-Q/RT}$, where Q is the activation energy to cause diffusion to occur by whatever is the operative mechanism for the system (i.e., vacancy or interstitial diffusion) and R is the gas constant.

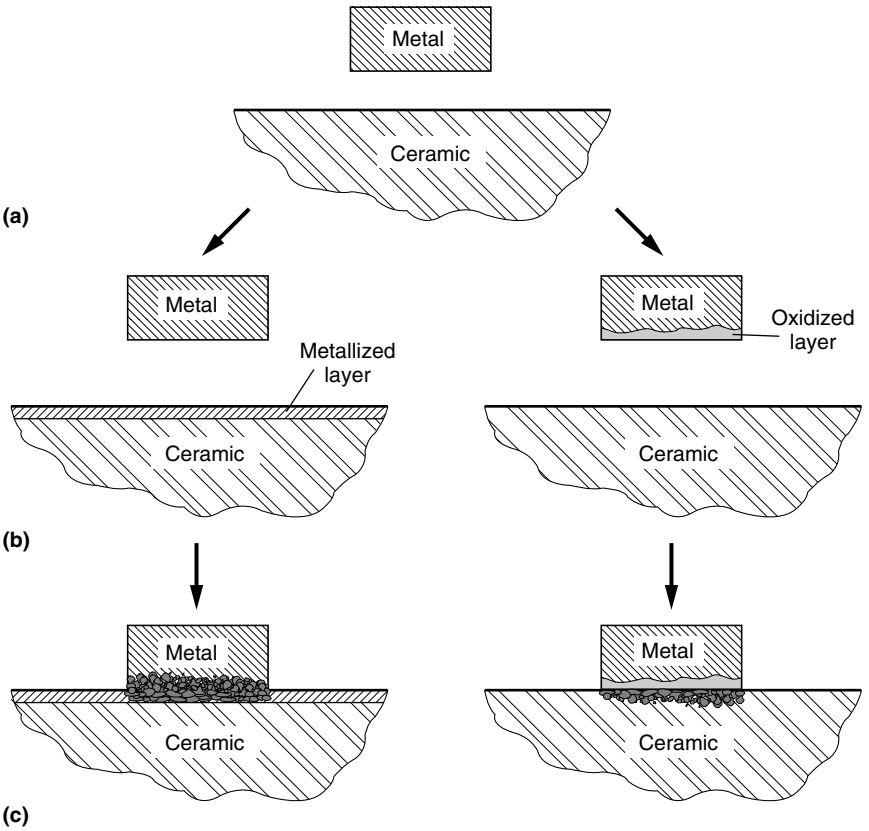

Figure 15.5 Schematic illustration of the stages of solid-phase bonding of metals to ceramics.

volume. Usually, the environment should be inert (e.g., a vacuum or a gas with a low oxygen activity). However, beneficial reactions can be induced by selecting the appropriate bonding environment. For example, oxygen enhances the bonding of Ag, Au, Co, Cu, Fe, Ni, Pd, or Pt to Al_2O_3, BeO, MgO, SiO_2, and ZrO_2. Table 15.2 lists some of the combinations of metals and ceramics that have been successfully diffusion-welded.

As a rule, diffusion in ceramics is inherently more difficult to induce than in metals, for two reasons. First, in ceramics, as opposed to metals, diffusion of more than one elemental species must occur simultaneously to maintain charge neutrality in ionically bonded ceramics and stoichiometry in all ceramics. This is made more difficult not only by the pure stochastic nature of the diffusion process but also by the fact that the non-metallic specie is usually much larger than the metallic one (e.g., anions are larger than cations in ionic compounds because of their net negative charge). Second, since diffusion is a temperature-driven process following an Arrhenius relationship, the relative rate is slow until the temperature reaches some large fraction (usually about 0.6–0.7%) of the absolute melting temperature. Since most ceramics are refractory by

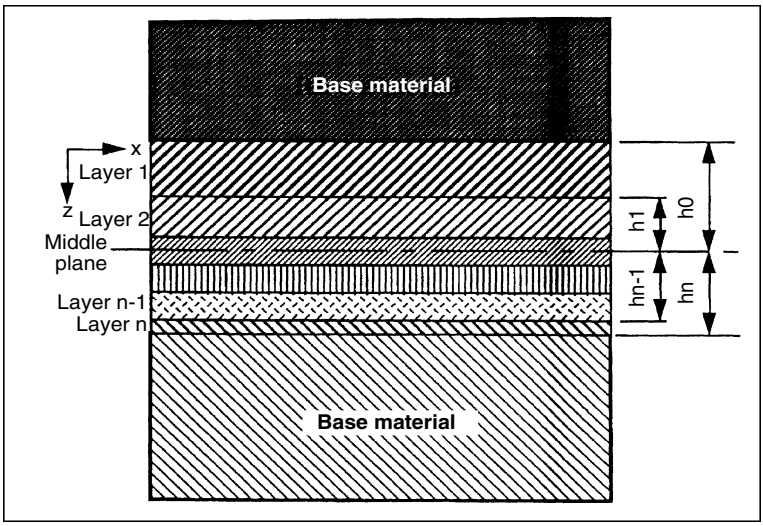

Figure 15.6 Schematic illustration of a functional gradient material (FGM) joint between a metal and a ceramic. (Reprinted from ''A model for designing functionally gradient material joints'', R.W. Messler, Jr., M. Jou, and T.T. Orling, *Welding Journal*, 74(5), 224s–229s, 1993, with permission of the American Welding Society, Miami, FL.)

Table 15.2 Some Successful Combinations of Metals and Ceramics that have been Diffusion Welded or Bonded Together

Al_2O_3–Al	Al_2O_3–Nb
Al_2O_3–Au	Al_2O_3–Ni
Al_2O_3–Cr	Al_2O_3–Nichrome
Al_2O_3–Cu	Al_2O_3–Pb
Al_2O_3–Fe	Al_2O_3–Pt
Al_2O_3–Kovar	Al_2O_3Steel
Al_2O_3–Mo	Al_2O_3–Stainless steel
	Al_2O_3–W
B_4C–Si	
BeO–Cu	
NbC–Nb, Ta, Mo, W	
SiC–Mild steel (using Co or Ni)	
SiC–Nb	
SiC–W or WC (using Pt or Ni)	
SiO_2–Cu	
ThO–W	
TaC–Nb, Ta, Mo, W	
UO_2–Stainless steel	
ZrC–Nb, Ta, Mo, W	
ZrO_2–Nb	

Reprinted from *Joining of Advanced Materials*, by Robert W. Messler, Jr., Butterworth-Heinemann (1993), Table 15.2, page 516, with permission of Elsevier Science, Burlington, MA.

their nature, the temperature necessary to cause a reasonable rate of diffusion in the ceramic could be too high for an inherently lower melting metal.

A special variation of diffusion welding for joining metals to ceramics is "electrostatic bonding." In *electrostatic bonding,* voltage (in addition to pressure, temperature, and time) is applied across the joint elements to effect bonding. The effect of the voltage is to enhance ionic conduction and induce strong electrostatic attraction between components. The process has been used for joining metals and semiconductors to various glasses (e.g., borosilicates) or, much less often, to glass-containing ceramics (e.g., Al_2O_3). (In fact, there is evidence that the healing of bones can be promoted by the application of either pure electric or pure magnetic fields, as such fields seemingly facilitate diffusion of ionic species in bone.)

Having achieved a bond during the joining of a metal and a ceramic, it is imperative to preserve it. Here, design is of crucial importance, especially for accommodating CTE mismatch-induced strains and stresses generated during cooling after joint fabrication, or from temperature excursions in service. This can be difficult in diffusion-welded joints since the pressure needed to cause bonding creates joints that are not suited to accommodating mismatches. Figure 15.5 shows that the effect of CTE mismatch on bond strength can be significant.

Other Non-Fusion Welding

Non-fusion, solid-phase welds have been successfully produced between metals and ceramics using various friction welding processes, including ultrasonic welding. Conventional friction welding has been used to join aluminum cooling elements to alumina chip carriers in microelectronics, while ultrasonic welding has been used to join 94–96 wt.% Al_2O_3 to moly-manganese-metallized Al_2O_3. The problem with friction welding, of course, is that ceramics have inherently poor plasticity. Nevertheless, some degree of macroscopic plastic deformation is known to facilitate, if not be necessary for, formation of friction welds.

Fusion Welding

Fusion welding, while rare for all the reasons given in Subsection 12.5.3, especially using high energy density processes, has been successfully used to join metals to ceramics. Despite the differences in CTEs, Al_2O_3 has been EB-welded to W, Mo, and some Fe–Ni–Co heat-resisting alloys using very high accelerating voltages (e.g., 90 kV) and low currents (e.g., 2 mA). Laser welding has also been used successfully to produce welds between metals and ceramics. Examples are given in Table 15.2.

15.3.5 Indirect Bonding Methods for Joining

The most common method of achieving high-integrity joints between metals and ceramics is to use a wide variety of intermediate bonding materials to overcome the

inherent chemical, as well as other property, incompatibilities of these two fundamentally different materials. These intermediate materials can be organic/polymeric adhesives, glasses, glass-ceramics, oxide mixtures (including cements and mortars), or metals. Actual bonding using some of these intermediates may be accomplished with the intermediate in either the liquid or solid state, depending on the intermediate and the process. In any case, the use of intermediates to effect bonding is called ''indirect bonding'' or ''indirect joining.''

Organic (polymeric) adhesives and inorganic (ceramic) adhesive cements and mortars were discussed in Chapter 12, Section 12.3, as were glasses or glass-ceramics for joining metals to ceramics. Ceramic and metal brazes were also discussed in Chapter 12, Section 12.4. Much of what applied there for joining ceramics to ceramics also applies here for joining metals to ceramics. The best joints are those developed after firing a suitable intermediate to fuse the joint elements together. Sometimes bonding is facilitated with these inorganic adhesives or cements by oxidizing the metal component. Metal intermediates are used as either solid-phase diffusion bonding agents (see Section 15.3.4) or as brazes or solders, with or without pretreatment of the ceramic surfaces to render them wettable. Alternatively, the surface of the ceramic can be metallized to facilitate wetting by the braze alloy or solder. The single greatest challenge of bonding ceramics to metals using additives or intermediates is, as usual, achieving wetting.

The special indirect bonding processes—''liquid-phase bonding'' and ''solid-phase bonding''—will be discussed next.

Liquid-Phase Bonding

Molten metals and glasses can both be introduced between the mating (faying) surfaces of a metal and a ceramic to create joints, provided that both base materials can be wetted by the chosen filler and the filler adheres and remains adhered (i.e., bonded) during post-fabrication cooling. The process is either brazing or soldering, depending on the melting temperature of the intermediate (brazes melt above 450°C (840°F) and solders melt below).

The ability of metals and glasses to satisfy these requirements differs significantly. Metals generally do not wet oxides as readily as glasses do, but metals are far less sensitive to the detrimental effects of thermal mismatch stresses generated during post-fabrication cooling. Few ceramics are wetted by molten metals, but most metals are wetted by molten glasses, in accordance with the usually large surface energy values for metals.

The usually poor wettability of ceramics is related to the non-metallic character of their bonding. In ceramics, with their localized ionic or covalent or mixed bonding, electron movement is restricted compared to metals (this restriction increases with increased ionicity). Thus, Pauling's electronegativity rules predict that oxides and fluorides are generally very ionic, and practice shows them to be the least wettable of ceramic families. Borides, phosphides, nitrides, and sulfides are less ionic and are, thus, often more wettable. Carbides can display some metallic characteristics, such as electrical conductivity, and often can be wetted well.

One common approach to promoting wetting is to make the inherently different materials more similar. There are two approaches for doing this: (1) pre-oxidize the

metal so that fabrication of a joint requires the easier formation of a similar oxide–oxide interface (for oxide ceramics); and (2) metallize the ceramic surface using electroless plating or various vapor deposition processes to require the formation of a metal-metal interface. Both approaches are used in practice (see Chapter 12, Section 12.4).

Two examples of metallizing, discussed earlier in reference to joining ceramics to ceramics using metallic braze fillers, are worth repeating here. The first is a process known generally as the "sintered metal powder technique," with the most common approach using Mo and debased Al_2O_3 in the process known as "moly-manganese" (see Subsection 12.4.3). Here, the alumina grains are held together by a glassy phase. When Mo is applied to the ceramic's surface as a powder (often mixed with MnO_2, Mn, or Ti) and fired in a reducing atmosphere, the glassy phase migrates into the metal powder and binds the particles to each other and to the alumina, thereby promoting wetting. Molybdenum and tungsten, with various metal oxides, are used for high temperature applications, while other approaches use mixtures with Rh, Fe, Ni, and Cr. Bond strengths can approach 70 MPa (10,000 psi) and higher. The second approach uses TiH_2 activation. Here, titanium hydride powder is applied to the ceramic surface before vacuum brazing. During brazing it dissociates at 350–550°C (662–1,022°F) and forms a wettable Ti surface.

A third approach is known as the "reactive- or refractory-metal salt technique." Here, the ceramic substrate is painted with a solution of a refractory or reactive metal salt, such as lithium molybdate. The painted substrate is dried and then treated at a high temperature to dissociate (i.e., reduce) the salt to a metal that bonds to the ceramic. Bonding occurs between the metal and the ceramic since deposition takes place atom by atom, not bulk to bulk, so that fundamentally different mechanisms operate. Besides solutions in various solvents, molten salts can also be used. In one form of this approach, TiO_2 and KCl (or NaCl) react to form $TiCl_3$ and KO (or NaO), at which point the $TiCl_3$ reacts to form Ti, which bonds to the ceramic by reacting with the substrate.

Other methods of metallizing a ceramic include sintering a finely divided mixture of metal and glass powder to the ceramic's surface to allow wetting of the metal particles by the braze, or applying a metal layer to the ceramic by chemical or physical deposition processes (i.e., CVD and PVD, respectively). Examples include sublimation and vaporization (or vacuum metallizing), sputtering, ion plating, and thermal (e.g., plasma or detonation) spraying.

Still another approach is using a braze filler that contains an active metal (such as Ti or Zr) to react with the ceramic. These are called "active-metal brazes" (see Chapter 12, Subsection 12.4.3). The drawback of such brazes is their poor ductility due to the formation of complex microstructures containing intermetallic compounds.

Besides brazing, metals and ceramics can be soldered together, although this is often not practical because of the intended high service temperature for which a ceramic may have been originally chosen. Here, the ceramic joint element must definitely be metallized. Soft-soldered ceramic-to-metal joints are useful when the manufacturing and service temperatures can be kept low. Thermal expansion mismatch is not much of a concern since temperature excursions are limited, and the soft solder alloy can yield to accommodate strain. A common approach is to fire a layer of Ag onto the ceramic at the joint faying surfaces at about 750–850°C (1,382–1,562°F). Sometimes the Ag is mixed

with glass to form a glaze to promote adherence. Silver-bearing Sn–Pb solders are then used to avoid dissolving the Ag metallizing layer.[7]

Figure 15.3 shows liquid-phase bonding between a metal and a ceramic schematically.

Solid-Phase Bonding

In principle, solid-phase bonding achieved by hot pressing using metal interlayers has two clear advantages: (1) it does not require that the bonding agent wet the ceramic and (2) the ductility of the pure metal bonding interlayers can more easily accommodate thermal expansion mismatches. If low-melting-point metals are used, fabrication temperatures can also be kept low, minimizing any chance of thermal degradation of the workpiece. The process and mechanisms of solid-phase indirect bonding are the same as diffusion welding (discussed in the previous subsection).

The most common interlayer to date is aluminum. It has been used to join Ti alloys to Al_2O_3, steel to Al_2O_3, and quartz to steel. For hermeticity or higher temperature service or caustic environments, however, aluminum is inadequate, and so Cu, Ni, and Ag have been considered.

Figure 15.4 schematically shows solid-phase bonding between a metal and a ceramic.

15.3.6 Functional Gradient Materials (FGMs) as Joints

Of special interest is the use of several interlayers of graduated metal–ceramic compositions to produce a joint between severely mismatched workpieces. This technique, developed by the Japanese in the 1980s, was described in the previous subsection as "functional gradient material" (FGM) joints. Techniques for producing graded layers include various methods for applying blended ceramic and metal powders, including thermal spraying, weld deposition (e.g., using laser-plasma hybrid welding), and, most recently, combustion synthesis. While relatively new, the technique offers great potential for joining traditionally difficult-to-join combinations (Messler *et al.*, 1995).

Figure 15.6 schematically illustrates an FGM joint between a metal and a ceramic.

15.4 JOINING METALS TO GLASSES

15.4.1 General Comments on the Challenges of Metal-to-Glass Joining

Glass-to-metal joints or seals (as they tend to be called) are important in electrical, vacuum, and some chemical applications. This combination of materials is important when (1) optical transparency is required to allow direct observation of some function

[7] This technique of using a solder, braze, or weld filler already containing a solute works if that solute is present at its solubility limit. This prevents further dissolution of this solute from a substrate.

or operation occurring within a system; (2) an infrared or visible laser must be allowed to pass through a window (e.g., as in a laser-guided weapon); (3) chemical stability is required; (4) it is necessary to achieve high vacuum (10^{-8} Torr or greater) and easily remove contamination; and, occasionally, (5) unique electrical, optoelectronic, or photonic properties and interconnection are required. The metal portion of the system is often there for structural purposes or to dissipate heat.

Glass-to-metal seals can be categorized in four types, as shown schematically in Figure 15.7. Type 1, "matched seals," are those in which the metal is sealed directly to the glass. The resulting stress is kept to within safe limits by selecting a glass and a

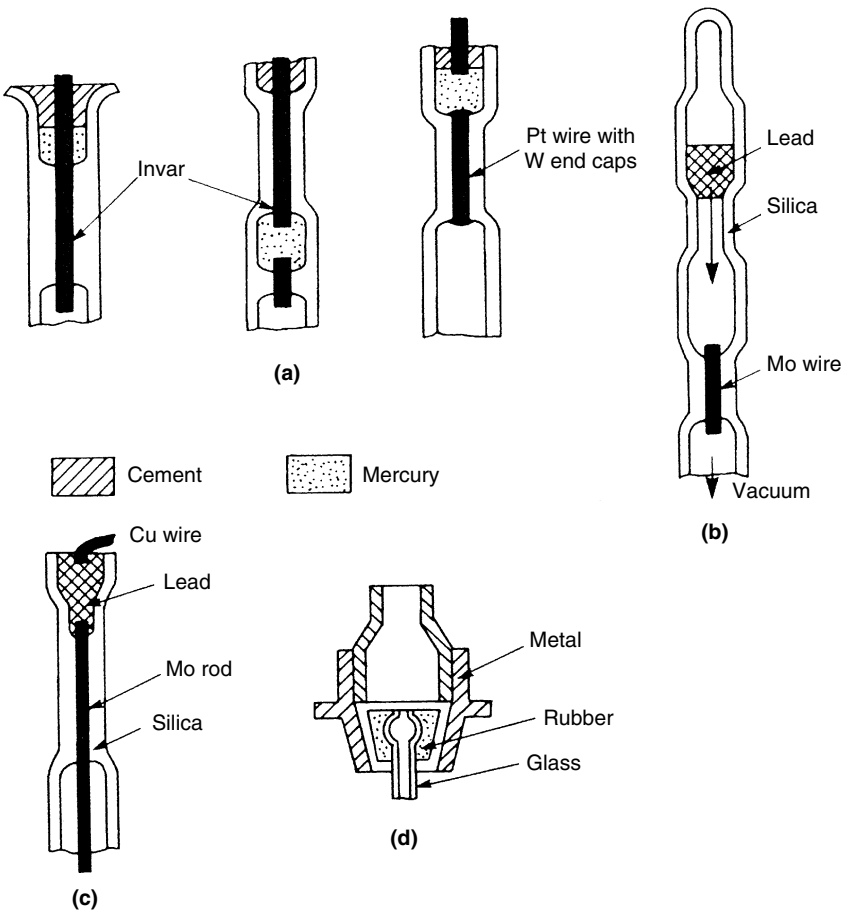

Figure 15.7 Schematic illustrations of the four basic types of metal-to-glass seals: (a) matched seals; (b) unmatched seals; (c) soldered seals; and (d) mechanical seals. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 15.2, page 526, Butterworth-Heinemann, Stoneham, MA, 1993, with permission from Elsevier Science, Burlington, MA.)

metal with coefficients of thermal expansion that are similar. Type 2, ''unmatched seals,'' are those in which the thermal expansion of the metal differs from that of the glass. The dangerously high stresses that would normally arise are avoided by using: (a) metal parts of very small diameters (so there is not much dimension over which the CTE acts); (b) ductile metals (which, by their yielding relieve some of the stresses arising from the CTE mismatch); or (c) intermediate glasses and graded seals (the final end members of which match the CTEs of the substrates or joint elements). Type 3, known as ''soldered seals,'' are those in which the metal member is soldered to a layer of metal previously applied to the surface of the glass by one of several methods (described earlier). Finally, Type 4, ''mechanical joints'' or ''mechanical seals,'' are those in which the joint between the glass and the metal components involves purely interlocking and/or frictional forces, as opposed to any chemical bonding forces. Often in metal-to-glass joining, hermeticity is more important than strength, provided some strength is available to maintain joint integrity.

15.4.2 Properties of Metal-to-Glass Seals

A metal that can be attached to glass to produce a gas-tight seal should conform to the following general requirements: (1) its melting point must be higher than the working temperature of the glass[8]; (2) sufficient quantities of the metal should be available in a clean metallurgical state (i.e., free from non-metallic inclusions); (3) it must be sufficiently ductile to enable it to be formed into wire or strip without mechanical defects (e.g., cracks); (4) the curves of coefficient of thermal expansion versus temperature for both the metal and the glass should, in the case of matched seals, follow one another closely over the intended use range; (5) no allotropic transformations, accompanied by marked changes in thermal expansion rate, should occur over the range of temperature to which the joint will be exposed (possibly −45–1,200°C or −50–2,000°F); (6) any layer of oxide formed in making the glass-to-metal seal should adhere firmly to both the metal and the glass; and (7) ease of joining to other metals by welding, brazing, or soldering is desirable and often essential.

Lists of suitable metals and alloys for use with low thermal expansion (''hard'') and high thermal expansion (''soft'') glasses are given in Tables 15.3 and 15.4, respectively.

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[8] The *working temperature* of a glass is defined as the temperature at which the glass reaches a viscosity in the range of 10^3-10^5 Pa-sec (10^4-10^6 poise), at which level the glass can be shaped easily yet retains its newly worked shape. Because glasses do not melt at a specific temperature or even over a specific range (since they are amorphous and soften continuously with increasing temperature), various viscosity ranges have been established for allowing various functions to be carried out. Other examples, besides working range, are annealing range ($10^{11.5}-10^{12.5}$ Pa-sec ($10^{12.5}-10^{13.5}$ poise), softening point ($10^{6.6}$ Pa-sec ($10^{7.6}$ poise), and melting range (5–50 Pa-sec (50–500 poise). The viscosity of water at 20°C, for comparison, is 0.001 Pa-sec (0.01 poise), where 1 pa-sec = 10 poise = 1 kg/mm/sec.

15.4.3 Glasses Used for Sealing to Metals

Many glasses possessing quite different physical properties are capable of wetting and, thus, fusing to metals. As a result, the only other requirement that needs to be considered is CTE matching. Table 15.5 lists some of the important physical properties of glasses and metals used successfully in seals. Notice that the CTEs of the mating pairs of metals and glasses are close, generally within $1-1.5 \times 10^{-6\circ}C^{-1}$ (as was given as a guide for matching CTEs earlier in this book).

15.4.4 Methods for Producing Metal-to-Glass Joints and Seals

Various methods for producing joints or seals between metals and glasses are described in the following paragraphs for the four principal types: (1) matched seals, (2) unmatched seals, (3) soldered seals, and (4) mechanical seals. These are shown schematically in Figure 15.7.

Matched Seals

The construction used for the current (power) leads of some lamps and vacuum tubes is typically of the matched type of glass-to-metal seal. The wires are surrounded by a flanged piece of glass tubing that was heated until thoroughly soft and then was squeezed around the wires by pincer-like jaws. This type of construction is usually termed a "pinched seal." It is the most common type of glass-to-metal seal.

In matched seals, alloys and glasses of similar coefficient of thermal expansion are used, so that the resulting joints are substantially free from induced strain and potentially destructive stresses. Metals or alloys in circular, disc, or tubular forms are typically used to minimize stress concentrations from sharp features.

Unmatched Seals

Pinched seals can be made between metals or alloys and glasses that are not matched in terms of their CTEs, provided the expansion mismatch is dealt with in some other way. There are essentially three ways. First, metal parts of very small dimensions (e.g., diameters typically less than 0.8 mm or 0.035 in.) can be used. This works because the total strain induced by mismatched CTEs depends on the length over which the CTE (in units of mm/mm/°C (in./in./°F)) acts. Small dimensions result in small strains, regardless of the difference in CTEs. Second, ductile metal (e.g., Cu, Ni, Pb, or even Mo) parts can be used because they distort under the induced stresses of mismatched CTEs, thereby shielding the brittle glass from stress buildup. Third, glasses of intermediate CTEs can be used to bridge the difference between the metal and the glass joint elements. Here, glass-to-glass bonds are made everywhere except between the final intermediate glass and the metal joint element.

The use of intermediate glasses ("graded seals") was quite common before the wide range of alloys and glasses listed in Tables 15.3 through 15.5 were known or available. Intermediate glasses were typically fluxes (or powdered blends) of easily

Table 15.3 Properties of Metals Suitable for Sealing to Low Coefficient of Thermal Expansion (CTE) or "Hard Glasses"

Metal	*Melting Point (°C)*	*Maximum Operating Temp. (°C)*		*$a \times 10^4$ (20°C–350°)*[a]	*Ultimate Strength (tons/ in.^{2})*	*Yield Stress (tons/ sq. in.)*	*Elongation (% on 100 mm)*	*Specific Electric Resistance (ohm/cm)*	*Thermal Conductivity (cals/aq cm/cm/ °C/sec)*
		In Vacuo	*In Air*						
Tungsten	3350	3000	300	4.4	99	85	4	5.6	0.38
Molybdenum	2450	2000	200	5.5	47	41	15–20	4.8	0.35
50% W, 50% Mo alloy	*ca.* 2800	2000	200	5.0	80	74	25–30	8.6	–
84% W, 12% Ni, 4% Co	–	–	–	6.8	–	–	–	–	–
Fernico I (54% Fe, 28% Ni, 18% Co)[b]	*ca.* 1450	*ca.* 1000	*ca.* 600	4.5	40	28–30	24	46	–
Kovar (54% Fe, 29% Ni, 17% Co)	*ca.* 1450	*ca.* 1000	*ca.* 600	4.7	38–40	25	32	44	0.04
				(39)[c]	(27)[c]	(26c)[d]			
Tantalum	2800	2500	–	6.5	–	–	–	15 · 5	0.13

[a] The usual symbol *a* is used throughout in referring to the linear coefficient of thermal expansion.
[b] *J. App. Physics,* 1941, 12, 698.
[c] The figures in brackets were determined on specimens of iron–nickel–cobalt alloys made by pressing and sintering pure metal powders and subsequently fabricating into wire.

All temperatures, unless otherwise stated, are expressed in degrees Celsius.

Data taken from T. Takamori, "Solder Glasses," *Treatise on Materials Science and Technology,* Vol. 17, Glass II, M. Tomozawa and R.H. Doremus (Eds.), Academic Press, New York, 1979, page 186. Reproduced by kind permission of the Society of Glass Technology.

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Table 15.4 Properties of Metals Suitable for Sealing to High Coefficient of Thermal Expansion (CTE) or "Soft" Glasses

Metal	*Melting Point (°C)*	*Maximum Operating Temp.*		$a \times 10^4$ *(20°C–350°)*[a]	*Ultimate Strength (tons/sq. in.)*	*Yield Stress (tons/sq. in.)*	*Elongation (% on 100 mm)*	*Spec. Elect. Resistance (ohm/cm)*	*Thermal Conductivity (cals/aq cm/cm/°C/sec)*
		In Vacuo	*In Air*						
Platinum	1750	1600	1400	9.25	8–9	*ca.* 2	30–40	10.6	0.166
Copper	1083	400	150	17.8	16–17	9–10 (50–60)	30	1.75	0.920
Nickel	1452	900	400	14.5	34	16 (35)	25	7 · 5–10.0	0.14
Iron	1530	500	200	13.2	15–17	8 (40–50)	30	9.6	0.17
50% Ni, 50% Fe alloy	–	1000	–	9.5	35–36	22–25	25–28	49	0.025
26% Cr–Fe alloy	–	1000	1000	10.2	39–41	28–30 (35)	18–20	68	0.03

[a]The elongation figures in brackets were determined on specimens of larger diameter over a gauge length $= 4\sqrt{\text{area}}$.

Data taken from T. Takamori, "Solder Glasses," *Treatise on Materials Science and Technology*, Vol. 17, Glass II, M. Tomozawa and R.H. Doremus (Eds.), Academic Press, New York, 1979, p. 187. Reproduced by kind permission of the Society of Glass Technology.

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Table 15.5 Physical Properties of Metals and Glasses Used in Seals

Combination	*Metal*	$a \times 10^6$ *(Metal)*[*]	*Glass*	$a \times 10^6$ *(Glass)*[*]	*Annealing Range (Glass)*[**] *(°C)*		*Color of Seal*	*State of Strain (annealed seals viewed at right angles to longitudinal axis)*	*Diameter of Wire (2a) (mm)*	*Diameter of Sheetbed Single Wire Seal (2b) (mm)*	*Ratio b/a*	*Maximum Tensile Stress (after normal annealing (kg/cm²)*
1*a*	Tungsten	4·4	Corning 720MX	3·3	553°	510°	Straw to light brown	Severe compression	2·5	7	2·8	480 rl[†]
1*b*	”	”	Pyrex	3·2	–	–	” ”	” ”	1·0	4.1	4·1	520 rl[†]
2*a*	Molybdenum	5·5	Corning 705AJ	4·6	496	461	Light brown	Severe compression	2·5	7	2·8	215 rl[†]
2*b*	”	”	Corning G71	5·0	513	479	” ”	Slight tension	2·5	7	2·8	02 cl[†]
4*a*	Platinum	9·4	G.E.O. X4	9·6	520	450	Bright metallic	Severe tension	0·8	4·1	4·1	000 cl
5*a*	26% Cr–Fe	10·2	Corning G5	8·9	429	404	Greenish grey	Compression	2·5	7	2·8	128 rl[†]
6*a*	Fernico I	–	Corning 705AJ	4·6	496	461	Grey	Compression	2·5	7	2·8	118 rl[†]
6*b*	(64% Fe, 28% Ni, 18% Co)		Corning 705AO	5·0	495	463	”	Slight tension	2·5	7	2·8	59 cl[†]
7*a*	Fernico II (54% Fe, 31% Ni, 15% Co)	–	Corning 705AO	5·0	495	463	Grey	Strain free	2·5	7·5	3·0	About 10[‡]
8	British Kovar type alloys, e.g. “Nicosel,” “Telcoseal No. 1,” and “Darwin’s F” alloys	4.5	B.T.H. C40	4·8	497	–	”	Slight compression	1·0	3·0	3·0	0–100 rl (according to metal)
			G.E.C. FON	5·1	500	440	”	Strain free	2·5	7	2·8	12 rl
9*a*	Fernichrome (37% Fe, 30% Ni, 25% Co, 8% Cr)	9·95	Corning G5	8·9	429	404	”	Very slight tension	2·5	7	2·8	14 cl[†]
9*b*		–	Corning G8	9·2	510	475	”	Compression	–	–	2·8	84 rl[†]
10	50/50 Ni–Fe Alloy	9·5	G.E.C. L1¶	9·1	410	350	”	Slight tension	1·04	3·75	3·6	34 cl
15	Copper	17·8	Many glasses if suitably shaped	3·5–10·2	–	–	Red to gold	Strain free a fraction of a millimeter from joint	–	–	–	–

rl. signifies in radial direction.
cl. signifies in circumferential direction.
[*] a = mean coefficient of linear thermal expansion between 20° and 350°, except for Corning glasses, where range is 0–310°.
[†]Values taken from Hull and Burger’s paper.
[‡]Values taken from Hull, Burger, and Navias’ paper.
Data taken from T. Takamori, “Solder Glasses,” *Treatise on Materials Science and Technology*, Vol. 17, Glass II, M. Tomozawa and R.H. Doremus (Eds.), Academic Press, New York, 1979, page 187.
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fusible (i.e., low-melting) glasses containing a moderate proportion of silica, lead oxide, boric oxide, and alkalis. The most popular is called "Pantin glass," which contains 38.5 wt.% SiO_2, 53.23 wt.% PbO, 0.80 wt.% CaO, 0.38 wt.% MgO, 0.45 wt.% Na_2O, and 5.45 wt.% K_2O.

Cracking in seals made in this manner is reduced because stresses at the glass–metal boundary are lowered by (1) the lower temperatures required to make the seals; (2) the thin fusing layers (to reduce stresses); and (3) less oxidation of the metal element.

Soldered Seals

To overcome difficulties experienced in sealing metals directly to glass, joints can be successfully made by depositing a metal coating on the glass (say by CVD or PVD) and then soldering between this metal coating and the metal component of the seal. In the earliest and still most common method, the metal coating was applied by painting the glass surface with a suspension of fine metal powder or with such compounds as platinum chloride or silver oxide. This coating is then heated to deposit the metal by chemical reduction. Newer options for applying a metal coating include (1) heating a film of silver or platinum in liquid suspension; (2) evaporation or deposition in a vacuum; (3) cathodic sputtering; (4) thermal spraying; (5) deposition from aerosol; and (5) reduction of a metallic oxide. Subsequent soldering is fairly conventional (see Chapter 8).

Obviously, In-based solders (Chapter 8, Subsection 8.5.10) can be used to join metals to glasses, as In has the unusual attribute of wetting virtually everything!

Mechanical Seals

Several clever mechanical methods of achieving glass-to-metal seals have been successful. In each, the joint or seal is obtained through mechanical interlocking as opposed to chemical bonding, often relying on extremely tight (even interference[9]) fits. In one type of mechanical joint, called a "ground joint," a metal pin (often made from low-CTE Invar) is precisely ground to fit tightly into a tapered hole in the glass (typically fused silica). Sealing is ensured by using mercury entrapped with an inorganic cement. Several possible designs are shown in Figure 15.7. A second method involves producing a metal annulus with lead (Pb). The lead is preplaced, and then the glass is heated to collapse tightly around the metal component of the joint, and, finally, the lead is melted to create a tight seal. This approach is shown in Figure 15.7c. Other methods for mechanically joining rely entirely on interlocking design features and use no filler to effect the seal. An example is shown in Figure 15.7d.

Perhaps one of the most common methods for joining glass to metal (or wood, for that matter) is through the use of rubber grommets, O-rings, or sealing strips contained in metal (or wood) tracks or frames. A prime example can be seen in Figure 15.8, where the installation of glass into a wood window sash is shown.

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[9] An interference fit is obtained when a male part or part feature is larger than the female part or part feature into which it is to be inserted. An example is a rivet that has a diameter slightly greater (0.125–0.25 mm or 0.005–0.010 in.) than the hole into which it is to be installed. Interference-fit rivets and other parts induce a compressive residual stress that helps to resist fatigue normally associated with the concentration of stress around fasteners and fastener holes.

Figure 15.8 The mounting and sealing of glass in high-quality wood window frames is accomplished using one or more of the following thin-gauge formed sheet-metal spring strips and elastomeric gaskets for shock absorption, differential thermal expansion and contraction accommodation, and sealing against air and water intrusion. (Courtesy of Pella Corporation, Pella, IA, with permission.)

15.5 JOINING METALS TO POLYMERS

15.5.1 General Comments on Challenges of Joining Metals to Polymers

The joining of metals to polymers is challenging because the atomic structures of the two materials differ so greatly, and, thus, their properties are quite different. The significant structural differences suggest joining methods that rely principally on mechanical forces to avoid intermixing of the dissimilar materials (e.g., mechanical fastening or integral attachment, and adhesive bonding). However, the viscoelastic behavior of polymers versus the elastic (plastic) behavior of metals (see Figure 13.2) means that stresses imposed by mechanical fasteners or attachments must be kept low; otherwise severe deformation and loss of integrity can occur.

As in all joining of dissimilar materials, joining of polymers to metals can be facilitated by making the materials appear more alike. For this combination, the most common approach is to metallize the surface of the polymer, while another method is to fill the polymer with metal powder. Either of these allows soldering of the metallized layer to the metal component, often using fusible alloys.

15.5.2 Methods for Joining Metals to Polymers

As mentioned above, there are three ways of joining metals to polymers: (1) mechanical joining, using fasteners or integral attachment features; (2) adhesive bonding; or (3) soldering of metallized polymers.

Mechanical Fastening and Integral Attachment

Polymers can be joined to metals by mechanical means using fasteners or interlocking design features that are integral to the joint elements. As in joining polymers to one another mechanically, joint and fastener or interlocking feature design must consider the viscoelastic nature of the polymeric material to preclude localized cold flow and/or stress relaxation under sustained loads or stresses. Suitable fasteners include screws, bolts, rivets, and pins, as well as eyelets and grommets. Each type of fastener should have broad load-bearing surfaces (e.g., fastener heads, feet, faces, and/or washers) in order to prevent unwanted viscoelastic cold flow. Holes can be sleeved with threaded or unthreaded inserts. In any case, applied stresses must be kept low.

The most common approach to joining using designed-in features is to take advantage of the polymer's inherent high elasticity and resilience, using mechanical snap-fits. Originally, this technique was seen in inexpensive assemblies such as plastic toys, for example, with metal axles snapped into plastic clevises on cheap toy cars and trucks. Today, these same properties are taken advantage of in the snap-fit assembly of computer peripherals (e.g., "mice," keyboards, housings), cell phones, handheld remote control units, lawn and garden equipment, automobile trim, and many other consumer products. This is part of an aggressive and growing design-for-assembly philosophy; snap-fits facilitate assembly and automated manufacturing, as needed assembly motions are simple.

Adhesive Bonding

Metals can be joined to both thermosetting and thermoplastic polymers through the use of synthetic polymeric adhesives. The bonding to the metal side of the joint results from some combination of microscopic mechanical interlocking and weak chemical bonds (by surface adsorption), with mechanical interlocking often predominating. Obviously, on the polymer side of the joint, the bonding is almost strictly chemical (of both primary and secondary bonding types as well as polymer-chain entangling facilitated by interdiffusion).

In adhesive bonding of metals to polymers, the adhesive should be matched primarily to the type of polymer (e.g., thermosetting adhesive for thermosetting poly-

mers, thermoplastic adhesive for thermoplastic polymers), but the adhesive must also be compatible to the metal adherend in the joint. A good general practice is to precondition the surface of the metal with the active agent used in the adhesive, often by diluting some of the adhesive in a suitable solvent and painting (or otherwise applying) it to the surface of the metal where bonding is to occur. This is properly called a ''priming'' step (see Chapter 5). For metal-to-polymer bonding, epoxies are especially widely used, but cyanoacrylates and pressure-sensitive adhesives are gaining in popularity. In all cases, adhesives should be selected carefully, considering the application environment, and preparation of both joint elements (or adherends) must be carried out properly and carefully.

Soldering

In many electronic applications (e.g., printed wire boards and electronic packages), metals and polymers are joined to one another by soldering. This often occurs after the polymer surface has been metallized, usually with copper but also with Al, Ni, or Au. The metallized ''pad'' is then soldered to the metal lead (for leaded components) or castellation (for leadless components, which themselves may be polymers, metal, or ceramics). Because metallization of the polymer is well described in references on electronics manufacturing (see the bibliography at the end of this chapter), it will not be discussed here. Suffice it to say general methods include chemical or physical vapor deposition and thermal spraying. Metallized layers can be Cu, Sn, or Sn-Pb solder alloys, or Al, Cr, Ni, or Mo. The primary mechanism for adhesion of the metal layer to the polymer substrate is mechanical interlocking into microscopic asperities (sometimes enhanced by surface pretreatments such as etching). Adhesion between the metallized layer and the solder is partly mechanical but ought to be primarily metallurgical.

Solders are selected based on the application demands, but are largely Sn–Pb compositions. The greatest demand placed on these joints is usually the stress and strain caused by mismatch of coefficients of thermal expansion between the metal and the polymer. These mismatches can and do become significant, and joint failure can and does occur.

Figure 15.9 shows how polymers can be joined to metal or wood in modern office furniture.

15.6 JOINING METALS TO COMPOSITES

15.6.1 General Comments on the Challenges for Joining Metals to Composites

The need to join metals to composites is growing. The reason is that both metals and composites are, for the most part, selected for their particularly attractive mechanical properties for structural applications. Properties such as high strength at minimal weight; high stiffness at minimal weight; resistance to the propagation (even if not the nucleation) of structural damage in the form of cracks; and other, more specialized functionally specific properties call for these materials, often in combination to keep

Figure 15.9 Metal-to-polymer joining is used in modern office furniture. Here, as just one example, the molded plastic arm caps of this office leap chair (top) are attached to a formed sheet-metal plate (bottom) by both self-tapping screws in molded posts in the arm cap and by adhesives (seen as light-colored residue). (Courtesy of Steelcase, Inc., Grand Rapids, MI, with permission.)

costs to a minimum. Besides reducing the cost of raw materials, the combination of metals and composites can reduce manufacturing and fabrication costs and facilitate repair, as composites can be difficult to repair.

Because composites are almost always used for their superior mechanical properties, the need for joints that can sustain high loads and stresses is extremely important.

The special challenges posed by the joining of metals (or other monolithic materials) to composite materials arises largely from the variety of composites, including their matrix materials and the material type and form of their reinforcements. Organic/polymeric, metallic, intermetallic, ceramic, and carbon types of composites all pose different problems and so are treated in separate subsections below.

15.6.2 Joining Metals to Polymer-Matrix Composites

There are generally two options for joining metals to composites with organic or polymeric matrices: (1) mechanical fastening and (2) adhesive bonding. A third option is rivet-bonding, which can, in the right application, offer the advantages of both approaches. Mechanical fastening, rather surprisingly, is still the more common method for joining, but adhesive boding is gaining—slowly. Rivet-bonding is restricted primarily to high performance applications, such as in aerospace and automobiles.

Mechanical Fastening

Advanced polymer-matrix composite materials have very different properties from the metals they tend to replace, but they are increasingly being used in high-performance structures such as aircraft and selected high performance and/or upscale automobiles, and increasingly (albeit still minimally) in civil structures such as buildings and bridges. Figure 15.10 shows a structure in a modern aircraft in which a metal is joined to a polymer-matrix composite. Composites often reduce the number of structural components needing to be joined because of how easily they can integrate geometric features into a single part traditionally found in multiple parts (e.g., integral stiffeners in aircraft skins). Even though composites offer alternative joining methods (e.g., adhesive bonding), mechanical fastening still predominates.

Composite materials differ from monolithic materials by not being as ductile (i.e., they exhibit only elastic rather than elastic-plastic behavior) and by being inherently anisotropic for many forms of reinforcement. Mechanical joining of metals to organic/polymeric-matrix composites usually involves fasteners, although integral design attachment features could certainly play a role (Messler and Genc, 1998). Mechanical fasteners used with polymer-matrix composites carry or transfer shear loads through the joint. They typically develop clamping forces, however, and resist loads at the joint that act in the through-the-thickness direction, even if these are developed secondarily through bending or torsion or other complex loading. This turns out to be the weakest direction in most composites and in all laminated composites.

For the foregoing reasons, fasteners must be carefully designed and selected for metal-composite joining, considering several factors. First, galvanic compatibility must

Figure 15.10 An example of joining between metal and a polymer-matrix composite component in a modern aircraft. Here, epoxy–graphite composite control surfaces are shown bonded in a secondary bonding operation to machined Ti alloy forgings in an F14 fighter aircraft. (Courtesy of the Northrop–Grumman Corporation, El Segundo, CA, with permission.)

be addressed. When metal fasteners are coupled with composites containing graphite reinforcements and the joint is exposed to a corrosive environment, graphite's low electrical potential causes the fastener to act as an anode and corrode, often very rapidly. Current density is the best indicator of compatibility, as shown in Figure 15.11. Titanium and its alloys (e.g., Ti–6Al–4V), Fe–Co–Cr multiphase alloys (e.g., MP159 and MP35N), and Ni-based Alloys 600 and 718 are compatible with graphite fiber-reinforced composites, showing essentially no corrosion after 500 hours in 5% salt-spray testing. Some corrosion-resistant steels (e.g., A286, PH13–8Mo, PH17-7, 301, 304, and 316) are also acceptable for use with graphite–fiber composites. Monel alloys, several common corrosion–resistant 400-series stainless steels (e.g., 400, 405, and 440), and aluminum and its alloys are not compatible with graphite and should not be used in combination with such composites. Even when fastener materials are compatible, polymeric sealants are generally employed to prevent incursion by the corrosive medium.

Second, pull-through failures must be considered and guarded against. When through-the-thickness forces act on a fastened composite joint, they can literally pull the fastener head or foot through the composite laminate. The net failure load is

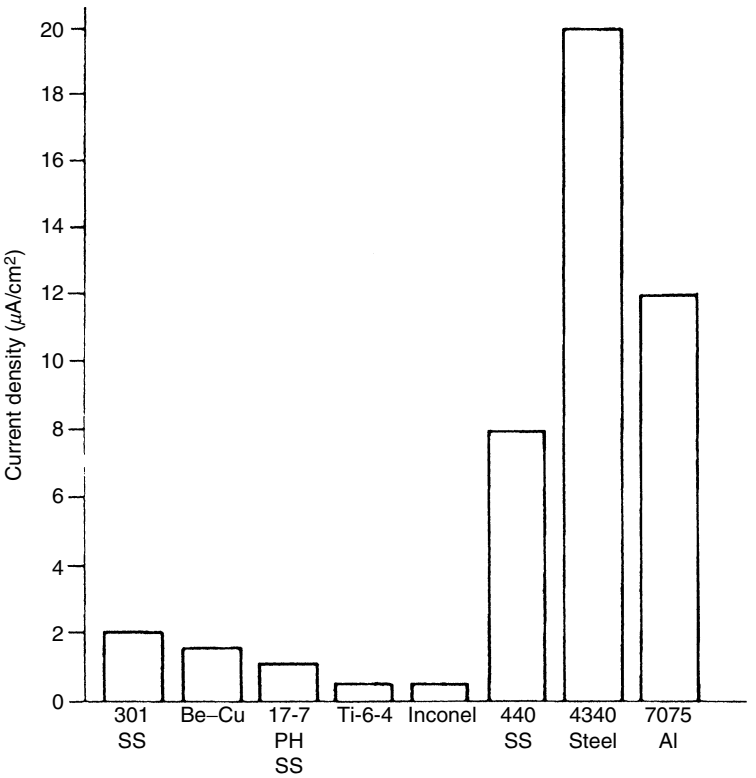

Figure 15.11 A plot of the current density for metals coupled to graphite as an indicator of the potential for galvanic corrosion. (Reprinted from *Joining of Advanced Materials*, Robert W. Messler, Jr., Fig. 15.3, page 529, Butterworth-Heinemann, Stoneham, MA, 1993, with permission of Elsevier Science, Burlington, MA.)

influenced by bending moments, in-plane stresses, and dynamic effects that act in combination with the through-the-plane shear stress to lower that failure load. Structures joined with shear, flush head, and blind fasteners are particularly susceptible to this kind of failure. Pull-through strength can be improved by using fasteners with larger bearing surfaces. Tension rather than shear head fasteners should be used if pull-through strength is critical.

Third, loss of fastener preload must be considered. The viscoelastic nature of the matrix of polymeric composites can lead to the loss of the preload needed by certain fasteners (e.g., bolts) for them to function properly. This phenomenon is called *stress relaxation*. Loss of preload due to stress relaxation can be minimized by using large load-bearing areas on the fasteners or by using washers with bolts and nuts and even certain types of so-called "two-piece" rivets (see Chapter 3, Subsection 3.4.3). Other problems with preload can arise from volume changes in a polymer matrix due to environmental effects, such as swelling of certain thermosetting types (e.g., epoxies) from water absorption.

Fourth, any tendency toward fastener rotation must be considered. Fastener cocking (as opposed to turning under torque installation, known in a joint as "fastener rotation") leads to nonuniform bearing contact between the fastener shank and the fastener hole. At these highly loaded points, the composite can fail (often by delamination of plies in laminated composites). Fasteners with larger bearing areas resist cocking forces and retard undesired fastener rotation.

Fifth, galling of threaded fasteners must be considered. Galling and seizing can occur with bolts and nuts. This can lead to improper installation (e.g., cocking or insufficient preloading). To prevent galling, dry film lubricants are used.

Sixth, damage to the composite during fastener installation must be considered and guarded against. Some fasteners (especially metal fasteners) damage polymer-matrix composites. Damage occurs when the clamping stress exceeds the compressive strength of the laminate, at which point radial expansion of the fastener hole (from expansion of the fastener's shank) delaminates or buckles composite plies. Impact forces can also delaminate a laminated composite structure, or free-turning fasteners can abrade or splinter the composite surface. Current design practice is to avoid interference fits without using protective sleeves, fasteners without adequate bearing area, or rivets and blind fasteners that expand radially during their normal installation. Conventional rivet guns that rapidly hammer rivets to cause upsetting should also be avoided.

Adhesive Bonding

Many adhesives that bond well to the base resin can be used to bond polymers reinforced with such materials as glass fibers or synthetic high-strength fibers (e.g., Kevlar) to metals. For thermosetting matrices, epoxies work well. For thermoplastic matrices, hot melts work well. Cyanoacrylates also work well for both types. The polymeric (composite) and metallic adherends must be properly prepared, of course.

Rivet-Bonding

The benefits of mechanical fastening and adhesive bonding can be combined by rivet-bonding polymer-matrix composites to metals. This hybrid joining process is discussed in Chapter 10, Subsection 10.4.2. Let it simply be said here that the benefit of this process is the improvement to peel strength, especially important for laminated composites.

15.6.3 Joining Metals to Metal-Matrix or Ceramic-Matrix Composites

Metals can be joined to metal-matrix and ceramic-matrix composites much as they can to their monolithic counterparts. Options, in decreasing order of preference, include brazing, adhesive bonding, and mechanical fastening. For low-load applications exposed to low service temperatures, soldering is another less common option. For metals that are being joined to a metal-matrix composite (MMC), where the

metals or alloys are the same or compatible, non-fusion and fusion welding are possible. Some diffusion welding is possible for joining metals to ceramic-matrix composites (CMCs).

In current practice, the major consideration in joining metals to MMCs or CMCs is minimizing damage to the reinforcement due to thermal degradation, adverse chemical interaction, or adverse mechanical effects (e.g., breakage).

Joining to MMCs

Welding by solid-phase diffusion, friction, resistance spot, or high energy density fusion processes (e.g., EBW, LBW, and PAW) is possible between metals and MMCs where the matrix is compatible with the monolithic metal joint component. It is desirable to minimize the heat input to the joint to minimize adverse reactions between the reinforcement and the matrix in the heat-affected zone, as well as minimize thermal degradation (if not obliteration!) of the reinforcement in any fusion zone. For this reason, non-fusion processes, especially those that minimize or localize heating at the joint faying surfaces, are generally preferred. For non-fusion processes that use pressure, pressure localization and plastic deformation or gross upsetting must be minimized to avoid damaging continuous reinforcing fibers or laminations. Fusion processes that produce minimal melting and/or involve extremely rapid heating and cooling cycles, such as resistance spot or capacitor-discharge, are also viable options, however. The high energy density fusion welding processes of EBW, LBW, and, to a lesser extent, PAW have produced acceptable joints, provided reinforcement is not totally destroyed by vaporization within the superheated keyhole.

Brazing is probably the most common method for joining metals to MMCs. Normal brazing procedures are followed, except particular care should be exercised to prevent thermal damage to the reinforcement or reaction between the reinforcement and the matrix. Essentially any brazing process can be used, but localized heating methods (such as torches or infrared, induction, or resistance processes) may be preferred, depending on the particular composite reinforcement and matrix phases. For particle, whisker, or chopped fiber reinforcements versus continuous fiber reinforcements, heating damage is often less detrimental. Obviously, if mechanical loading will be low, or is of secondary importance, soldering can be used with little problem. The selection of filler for either brazing or soldering is based solely on the composition of the monolithic metal and the composite's matrix.

Adhesive bonding works well for joining metals to MMCs, with little or no risk to the reinforcing phase. However, in-service loading must be as close to pure shear or pure tension as possible to avoid peel or cleavage failures. Furthermore, service temperature must be limited to prevent adhesive degradation, and other degrading environments must be avoided or considered carefully.

In mechanical fastening, hole preparation is a special challenge for several reasons, some relating to the fastener hole's production and some to the fastener that is installed. Drilling can be difficult to accomplish at all or might result in excessive tool wear if the reinforcing phase is particularly hard (e.g., glass). In addition, care must be exercised to avoid damaging reinforcing fibers that are continuous, as

compromising continuity compromises properties. So-called "softened areas," devoid of reinforcement, are often designed into the joint area where fastener holes are to be drilled, or inserts are pre-installed during composite synthesis or fabrication.

Two excellent options for joining metals to MMCs are weld-bonding and weld-brazing, particularly if the welding process is resistance -spot or capacitor-discharge (percussion). Here, loading is spread by the adhesive or braze, respectively, and peel strength is enhanced by the spot welds while heating is minimized.

Joining to Ceramic-Matrix or Carbon-Matrix Composites

Brazing is by far the most common method used to join metals to ceramic-matrix or carbon-matrix composites. For the most part, the process is carried out exactly as it would be for monolithic metals to monolithic ceramics or carbon (see Section 15.3). There is usually little risk of thermal damage to the reinforcement in the ceramic if that reinforcement is metallic or ceramic. This is because the brazing temperature is usually sufficiently low to avoid thermal degradation or adverse reactions, and often the reinforcement itself is fairly refractory.

Adhesive bonding using synthetic polymeric adhesives works well with the same caveats (i.e., out-of-plane loading should be avoided (by design) and environmental limitations should be kept in mind).

Non-fusion welding, using friction (including ultrasound) or diffusion welding, is also possible. When these processes can be used, joint properties can be excellent.

Mismatch of CTEs must be carefully considered and dealt with for brazing and welding, and, to a far lesser extent, for adhesive bonding.

15.7 JOINING OF CERAMICS TO POLYMERS

The use of ceramics in combination with polymers is relatively rare except for electronic applications, and for these applications loading is usually relatively low. Therefore, except for the rare case in which a metallized ceramic would be soldered to a metallized polymer, the only really viable option is adhesive bonding using synthetic polymeric adhesives. The choice of adhesive is dictated by the nature of the polymeric joint component (i.e., thermosetting adhesives for thermosetting polymers, thermoplastic adhesives for thermoplastic polymers). To deal with expected differential CTEs, the adhesive might contain an elastomeric component to facilitate strain accommodation.

In the late 1990s, investigators at Virginia Polytechnic Institute, led by Garth L. Wilkes, grafted ceramics onto polymer chains, creating a new class of hybrid materials called "ceramers." These are considerably stronger, stiffer, and more solvent-resistant than conventional polymers and could be useful for making lightweight structures. Joining of these new materials, should they gain acceptance and proliferate, will be a challenge, but the chemistry of their synthesis may hold the key to better ways to bond polymers and ceramics macroscopically with "ceramer adhesives."

15.8 JOINING CERAMICS TO COMPOSITES

15.8.1 General Comments on the Challenges for Joining Ceramics to Composites

Except in electronic applications where ceramic chip packages or chip carriers are adhesively bonded to fiber-reinforced polymer (or FRP) substrates or boards, ceramics will likely only be joined to metal- or ceramic- or carbon-matrix composites. This is because elevated temperature service is an extremely likely requirement that would lead to the choice of these combinations of materials. This being the case, likely joining options are brazing, mechanical fastening, and welding (at least between ceramics and ceramic-matrix composites).

Adhesive bonding is also possible between ceramics and metal-, ceramic-, or carbon-matrix composites, provided the right adhesive can be found. For joining MMCs, synthetic polymeric adhesives could be used, but service temperatures would be severely restricted. For joining to CMCs, organic or inorganic adhesives (i.e., cements and mortars) could be used, with far less restriction on service temperatures for the inorganic adhesives. For joining to carbon-matrix composites, organic adhesives might be used and pyrolized (see Chapter 14, Subsection 14.6.4).

15.8.2 Methods for Joining Ceramics to Various Composites

The preferred method of joining ceramics to composites depends strongly on the matrix of the composite.

Joining Ceramics to MMCs

Brazing is almost certainly the process of choice for joining ceramics to metal-matrix composites (MMCs). The techniques and procedures are the same as those for joining monolithic ceramics to monolithic metals, relying on metallization of the ceramic, oxidation of the metal (matrix), or bonding through an interfacial reaction. Noble metal, active metal, and refractory metal brazes could all be considered. For the most severe temperature and loading environments, diffusion brazing should be considered.

Welding, especially by solid-phase diffusion (with or without the aid of an intermediate) is possible, just as it is between monolithic metals and ceramics (Subsection 15.3.4). Adhesive bonding using organic adhesives can again be used, but with the usual service temperature restrictions. Mechanical fastening is possible, but the brittleness of the ceramic severely limits loading. It also demands that loading not be concentrated and that bending and impact be avoided. The same precautions must be taken to avoid damaging the reinforcement in the MMC, as is usually the case in mechanically fastened composites.

Joining Ceramics to CMCs

Once again, brazing is the process of choice for joining ceramics to CMCs, using either active metal brazing alloys or ceramic braze compositions. Techniques are the same as for brazing ceramics to ceramics (see Chapter 12, Subsection 12.3.1, or Chapter 14, Subsection 14.5.6). Welding is possible, just as between monolithic ceramics, but with the added complexity created by the reinforcement (i.e., the risk of thermal degradation). In fact, thermal degradation of ceramic reinforcements and reaction between ceramic reinforcements and ceramic matrices is usually less serious than with metal-to-metal or metal-to-ceramic joining. This is because ceramics are inherently non-reactive.

Adhesive bonding using inorganic adhesives is certainly a viable option, just as with monolithic ceramics. Mechanical fastening, while possible, would be limited because loading would have to be limited; temperature serviceability would also have to be restricted compared to most ceramics.

15.9 JOINING POLYMERS TO POLYMER-MATRIX COMPOSITES

15.9.1 General Comments on the Challenges for Joining Polymers to Polymer-Matrix Composites

The combination of polymers and fiber-reinforced polymers (FRPs) or polymer-matrix composites is a common one, widely used in aerospace, growing in automobiles, and appearing in sporting equipment, architecture, and elsewhere. The problems encountered in attempting to join these materials are relatively minor, provided the resin matrix of the composite and that of the unreinforced polymer are of the same basic type (i.e., both are thermosetting or both are thermoplastic). Even if they are different, however, there are good joining options.

By far, the preferred method for joining monolithic polymers and FRPs is to use synthetic polymer adhesives. For thermosetting types, use thermosetting adhesives; for thermoplastic types, use thermoplastic adhesives; and for mixed combinations, use adhesive alloys of the mixed types. For thermoplastics to thermoplastic-matrix composites, solvent cementing is also an option, as is thermal bonding (both of which are actually welding processes). Both offer excellent joint strength and have been used in the most advanced military aircraft, including especially "stealth" fighters and bombers, for which polymeric materials are particularly attractive for their lower detectability.

While mechanical fasteners and integral attachment features are feasible, they have only been used sparingly, largely because of the viscoelastic deformation of the fastener hole or attachment feature itself, or because of the susceptibility to fastener pull-through. One attractive opportunity is to use fasteners that are themselves polymers (especially thermoplastics, because of their ability to be upset during installation), possibly even reinforced for added strength. Also, in terms of mechanical property compatibility, it makes little sense to use fasteners that are much stronger (or weaker) than the materials they are being used to join.

It is unlikely, although not impossible, that polymers might be joined to composites with metallic, ceramic, or carbon matrices. In such cases, adhesive bonding is again the preferred method.

15.9.2 Methods for Joining Polymers to Polymer-Matrix Composites

As mentioned previously, the principal method for joining polymers to polymer-matrix composites is adhesive bonding. For the special case of thermoplastic polymers to thermoplastic-matrix composites, thermal bonding or welding is also possible.

Adhesive Bonding

Unreinforced plastics can be joined effectively to reinforced plastics by using adhesives of the appropriate type (often identical composition). Thermosetting polymers should be adhesively bonded to thermosetting-matrix composites using thermosetting resin adhesives, with the most popular being epoxies and modified epoxies. Either one- or two-component types can be used, depending on the constraints on curing and final performance requirements. It is possible to enhance the strength of the adhesive slightly by mixing in some reinforcement. This obviously works best if the composite is not continuously reinforced. Likewise, thermoplastic polymers should be bonded to thermoplastic-matrix composites using thermoplastic resin adhesives, especially hot melts. Solvent cementing can also be accomplished, however, possibly with the need for additional resin at the bond line.

Dissimilar polymer types, whether reinforced or not, can also be adhesively bonded using adhesive alloys containing mixtures of thermosetting and thermoplastic components, possibly with elastomers added for flexibility. Details for adhesive bonding all of these materials are given in Chapter 13.

Thermal Bonding or Welding

Thermoplastics and thermoplastic-matrix composites can be welded or thermally bonded by causing local softening and applying pressure to cause interdiffusion or intermixing and molecular-chain entangling. Various friction methods as well as hot gas, hot bar, or other heating methods can be used, with one of the newest developments being friction stir welding (see Chapter 6, Subsection 6.5.3). It may be necessary to add some resin of the same composition as the composite matrix to the faying surfaces to promote bonding. Otherwise, resin starvation and poor bond integrity might result.

15.10 JOINING WOOD TO OTHER MATERIALS

As described in Chapter 14, Section 14.8, wood is a natural composite. It is widely used (still representing around 20% of all of the material used around the world each year!), by itself and in combination with other materials, including metal (especially steel and aluminum), glass, cement and concrete, and polymers (including a variety of plastics and rubbers). The preponderance of applications are in architecture, building construction, and furniture manufacture.

The two joining methods that predominate are mechanical fastening and adhesive bonding. Principal fasteners include specially designed nails, self-tapping screws, bolts (with or without nuts), and rivets. Adhesives need to be compatible with all adherends involved in the joints, but they often involve phenolics, epoxies, or cyanoacrylates. The reader is referred to Chapter 5 and specialized references on adhesives for specific recommendations.

Figure 15.12 schematically illustrates methods for joining wood to various other materials.

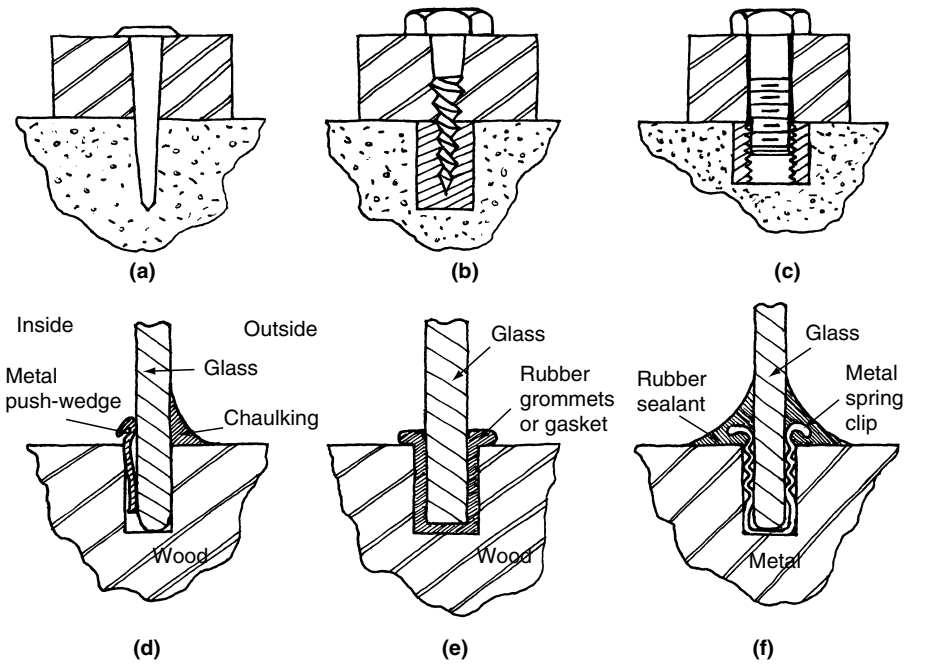

Figure 15.12 Schematic illustrations of some common methods for joining wood to various other materials, including wood to cement/concrete using masonry nails (a), lag screws into cast-in soft-metal (e.g., Pb) inserts (b), or bolts into cast-in internally, threaded anchor inserts (c); and wood to glass using metal push-wedges with or without elastomeric chaulking (d), rubber grommets or gasket strips (e), or thin-gauge sheet-metal spring strips with or without elastomeric chaulking (f).

15.11 JOINING CEMENT OR CONCRETE TO OTHER MATERIALS

Cement and concrete, like wood but to an even a greater extent, are used in construction more than in manufacturing; they represent upwards of half of the tonnage of all materials used annually worldwide. Also like wood, cement and concrete must be joined to other materials (or, actually, other materials usually need to be joined to them). Examples of these other materials include metals, glass, wood, and polymers (including plastics and rubbers). The largest application, by far, is in construction of buildings.

Specialized types of mechanical fasteners (including masonry nails, lag bolts, and screws) and a variety of integral attachments are used. Some of these integral attachments are really no more than fasteners (e.g., threaded studs) that extend from the cement or concrete (having been cast in place). Others are designed- and processed-in geometric features to allow interlocking.

Adhesive bonding is widely used, sometimes using cement itself as the adhesive (often employing some degree of mechanical interlocking to enhance attachment). A variety of specially formulated synthetic polymeric adhesives are gaining increasing popularity.

Figure 15.13 schematically illustrates some methods for joining various materials to cement and concrete.

15.12 LOGICAL AND ILLOGICAL COMBINATIONS REVISITED

As stated in Section 15.2, some combinations of dissimilar materials make little sense from a practical standpoint, particularly if the inherent properties of the component materials are drastically different. Examples include widely different strengths, widely different moduli, widely different coefficients of thermal expansion, and widely different temperature resistance (including melting points). It is simply good advice—and wise practice—to carefully consider, and even reconsider against, traditionally unconventional, if not illogical, combinations of materials in joints. New approaches to joining, however, could—and should—give cause for change.

SUMMARY

Dissimilar materials must frequently be joined to create hybrid structures in which diverse or even divergent properties, unattainable in individual materials, are required. Hybrid structures enable (1) minimization of weight, (2) improved damage tolerance in the joined structure, (3) optimized matching of properties to design needs, and (4) improved economy in basic material costs as well as the cost of fabricating especially difficult materials. The challenge posed to joining by dissimilar materials is obtaining sufficient compatibility to permit the materials to join in the first place and the joint to function in service in the second place. Compatibility must be chemical (i.e., atomic structure and bond type), physical (e.g., melting temperature and CTE response to temperature), and mechanical (e.g., stress-strain response and temperature stability

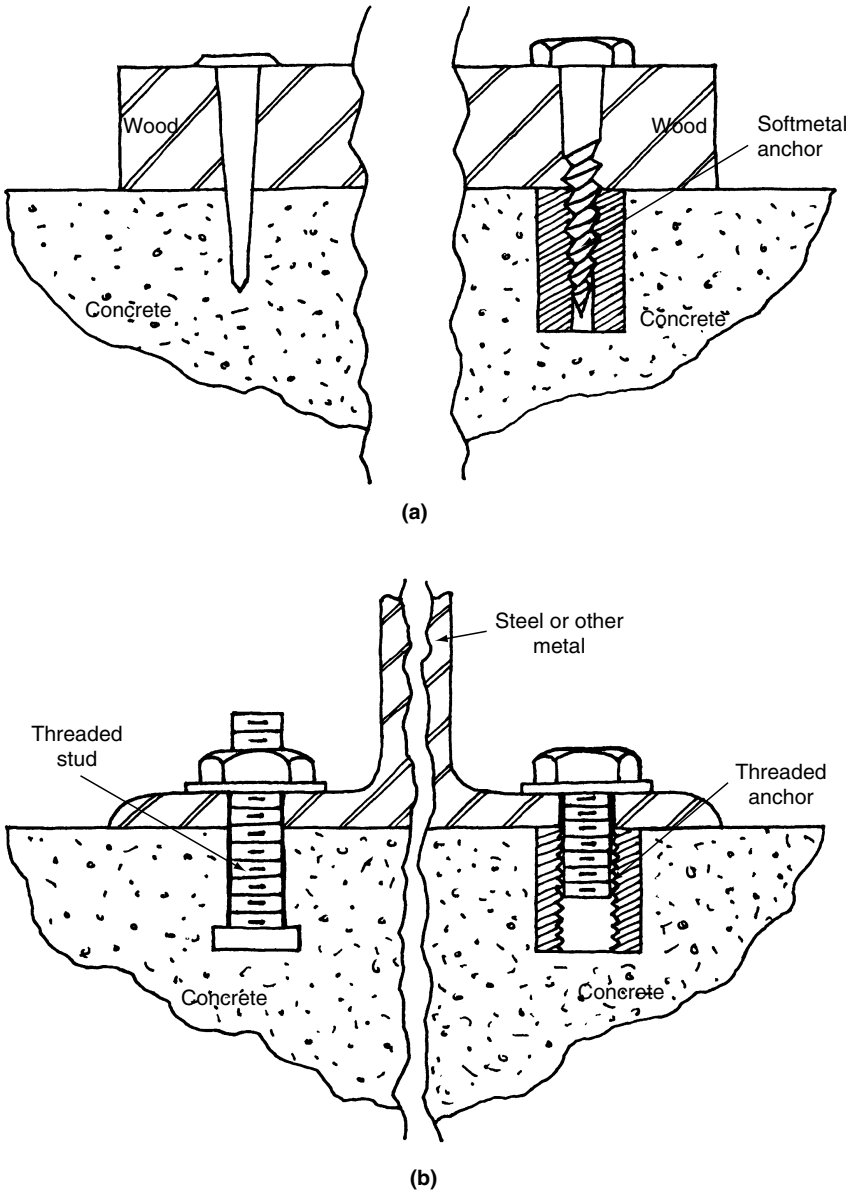

Figure 15.13 Schematic illustrations of some common methods of joining various materials to cement and concrete, including wood to cement/concrete using masonry nails or lag screws into soft-metal cast-in inserts or anchors (a) or cast-in threaded studs and nuts or bolts into internally threaded cast-in metal inserts or anchors (b).

of properties), and the closer the matches, the better. While every combination of the basic material types (i.e., metals and alloys, intermetallics, ceramics, glasses, polymers,

and composites) is conceivable, not every combination is practical or even logical based on drastic differences in fundamental structure and properties.

For joining metals to ceramics, the choices are (1) mechanical fastening by interlocking features or fasteners; (2) direct joining (or bonding) by non-fusion or, to a lesser extent, fusion welding; and (3) indirect joining (or bonding) using intermediates that include organic or inorganic adhesives (in adhesive bonding and cementing or mortaring, respectively), or metallic fillers that are melted to enable brazing or soldering or remain solid for assisting in diffusion welding. In mechanical fastening, stress concentration in the ceramic element of the joint must be minimized, and CTEs, in particular, must be matched or compensated for by joint and fastener design. In direct joining, solid-phase diffusion welding is possible and gives good results for some combinations. Other welding processes are possible, including friction, ultrasonic, and high energy density EBW and LBW. In indirect joining, liquid-phase and solid-phase bonding are possible using adhesives, braze or solder fillers, or intermediates for DFW. One key to facilitating the indirect joining of ceramics to metals (or other dissimilar materials) is to make the two fundamentally different materials appear less different. Oxidizing the surface of a metal, or metallizing the surface of the ceramic, accomplishes this task in the case of metal-to-ceramic joining.

When metals are joined to glass, the principal need is usually hermeticity, with mechanical strength being secondary. The brittle nature of glasses demands that CTEs be matched, or the metal joint element be kept small, or a compliant intermediate be used to accommodate differential strain. Joining methods predominantly include mechanical seals relying solely on interlocking, or achieving sealing through the use of a soft or melted metal interlayer (e.g., lead seal). Soldering of glasses with metallized surfaces to metals is also possible.

Metals can be joined to polymers simply by using polymeric adhesives, although mechanical fasteners are also used. With adhesives, here as elsewhere, the adhesive and the substrates should be the same polymer type (i.e., thermosetting or thermoplastic); otherwise the adhesive should be an alloy of both types. When fasteners are used, loading must not be permitted to concentrate to such high levels that cold flow by viscoelastic deformation occurs in the polymer. Once again, soldering can be accomplished by metallizing the surface of the polymer.

For joining metals to composites, one needs to consider the material making up the matrix of the composite and then select the joining process accordingly. For polymer-matrix composites, mechanical fastening and adhesive bonding are the preferred processes, and the hybrid process of rivet-bonding may be the best of all. For metal-matrix composites, welding with processes that minimize heat input and melting (such as DFW, RSW, capacitor-discharge welding, and FRW) are preferred. Brazing with metallic fillers is an excellent choice, and adhesive bonding and mechanical fastening are viable options. Weld-bonding and weld-brazing are also good choices for some applications where out-of-plane loading is likely. For ceramic-matrix composites, brazing with either metallic or ceramic fillers is preferred, with adhesive bonding an option.

For joining ceramics to polymers, adhesive bonding using organic polymer adhesives is the process of choice, with the selection of the adhesive to be used being

based on the polymer type. For joining ceramics to composites, polymeric adhesives are used to bond to polymer-matrix types. Brazing or solid-phase welding is used to join metal-matrix types, and ceramic and metal brazing or adhesive cementing is used to join ceramic-matrix types.

For joining polymers to polymer-matrix composites, adhesive bonding is clearly preferred, followed by mechanical fastening. Thermal bonding or welding is also possible for thermoplastic types.

Finally, joining of materials to either wood or to cement and concrete is a common need, particularly in construction, with mechanical fastening using specially designed fasteners and adhesive bonding being the preferred options.

QUESTIONS AND PROBLEMS

1. From a technical or technological standpoint, why is it so important to be able to join materials that are fundamentally different (i.e., dissimilar materials) to create modern designs? Why from an economic standpoint?
2. What makes the joining of dissimilar materials so challenging? Describe some of the specific challenges.
3. Are some combinations of materials more difficult to join than others? If so, what combinations are especially difficult? Why? If not, why not?
4. Why are some combinations of materials considered illogical? Give some examples of illogical combinations?
5. Why is it so important to be able to join metals and ceramics to one another? What properties of ceramics might be enhanced by joining to metals? What properties of ceramics are normally being sought in such a combination? What properties of a metal might be enhanced?
6. What are some "direct" methods for joining ceramics and metals? Why are such methods considered "direct"? What are some "indirect" methods for joining ceramics and metals? Why are such methods considered "indirect"?
7. One way to facilitate the joining of metals and ceramics is to make these two inherently dissimilar materials appear less different. What are the two most common approaches taken to accomplish this?
8. Why is it so desirable to be able to join metals and glasses? What properties of each material are the focus for enhancement by combining the two? Give some important application examples.
9. What are the four types of glass-to-metal seals? Describe each briefly. Give a practical, well-known example of each.
10. What properties of metals make them especially suitable for joining to glasses? What properties of glass make them especially suitable for joining to metals? What is it about these properties that leads to this "suitability"?
11. Describe the difference between "matched seals" and "graded seals." How, if at all, are these related? What is an "unmatched seal"? Why and how does it work?
12. Describe some clever ways of creating purely mechanical seals between metal and glass components. What allows these to work?

13. How are metals and polymers joined to one another by soldering? Why is this an important joining option—i.e., for what applications?
14. What are some of the special problems associated with producing structurally sound joints between metals and polymer-matrix composites? What techniques are used in practice?
15. What kinds of problems arise during the mechanical joining of metals to polymer-matrix composites using fasteners? How can these problems be made less serious, even if not eliminated, in practice? Do—or would—similar problems occur if joining were done using integral attachment features? Why or why not?
16. What are the preferred methods for joining metals and metal-matrix composites? Why are these methods preferred? What about joining metals to ceramic-matrix composites? What about joining metals to carbon-matrix composites? Give an example of where each type of joining might make sense, and name the materials involved in the joints.
17. How are ceramics usually joined to polymers? Give some examples of where such joining is important.
18. Differentiate between the preferred methods for joining ceramics to metal-, ceramic-, and carbon-matrix composites.
19. How challenging is it to join polymers to polymer-matrix composites? Explain your answer and state why this is an especially important joining combination.
20. When can polymers be thermally bonded to polymer-matrix composites? What are the advantages of such bonding?
21. Why is it reasonable to consider "solvent cementing" of thermoplastic polymers a welding more than an adhesive-bonding process?
22. When wood is to be joined to other materials, what determines how compatible the combination may be, in terms of chemical, physical, or mechanical properties? Give an example of wood combined with (a) metal, (b) ceramic (including cement or concrete), (c) glass, and (d) polymer. What process would probably be used for each of your examples?
23. When other materials are to be joined to cement or concrete, what determines how compatible the combination may be, in terms of chemical, physical, or mechanical properties? Give an example of (a) metal, (b) glass, (c) polymer, and (d) wood being joined to cement or concrete. What process would probably be used for each of your examples?

Bonus Problems:

A. How might advances in materials science change what were once considered extremely difficult joining problems between dissimilar materials? Give a couple of examples. Could such advances ever change what is now considered an illogical combination into a logical combination? Explain why or why not.
B. Why, from a basic materials science standpoint, is it fundamentally easier to get a glass to adhere to a metal than to get a ceramic to do so? Does this suggest any tricks for joining metals and ceramics? If so, what tricks? If not, why not?

C. Why is it that dissimilar materials can often be joined in non-traditional joining processes such as chemical vapor deposition (CVD) and physical vapor deposition (PVD) to produce atomic-level bonds, but not by more traditional joining processes like welding, brazing, or soldering?

D. Is there any reason one might treat joining a polymer to a ceramic substrate differently from joining a ceramic to a polymer substrate? Why or why not? If there is, from what would such differences arise?

E. Concrete is a complex material consisting of an aggregate (often quartz-based stones) in cement, as well as pores (air) and reinforcement (e.g., steel rods or mesh or glass mesh). After looking into some reinforced concrete used in modern construction, discuss the problems inherent in trying to get good adhesion between the various constituents of such concrete.

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Chapter 16

Joining Structures and Living Tissue

16.1 INTRODUCTION TO THE JOINING OF STRUCTURES AND LIVING TISSUE

At the beginning of this book, in Chapter 1, Section 1.1, joining was defined as "the act or process of putting or bringing things together to make them continuous or to form a unit." It was stated that as the term applies to fabrication, "Joining is the process of attaching one component, structural element, detail, or part to create an assembly, where the assembly of component parts or elements is required to perform some function or combination of functions that are needed or desired and that cannot be achieved by a simple component or element alone." Most significantly, it was stated, "At the most basic level, it is the joining of materials into components, devices, parts, or structural elements and, then, at a higher level, the joining of these components into devices, devices into packages, parts into assemblies, and structural elements into structures that is of interest here." Chapters 2 through 10 have dealt with the processes available for joining, while Chapters 11 through 15 have dealt with the challenges posed to the process of joining by various materials, in similar or dissimilar combinations. It is now time to consider the challenges associated with joining actual structures, beyond the always important and fundamental challenges that materials pose to joining.

As used here, "structures" refers to the physical entities being joined one to another. As such, structures always have size, shape, and internal details, often at the macroscopic as well as at the microscopic level. The size of the physical entities being joined ranges from what might be called typical (e.g., valve covers being joined to the head of an automobile engine, two-by-fours being joined into the wood frame of a house, electronic packages being joined to circuit boards, and circuit boards being joined into computers) to extremes of large or small. At one end of the size spectrum there is the joining of very large structural entities, like thick-section high alloy steel or stainless steel cast or forged pressure heads being joined to like-material reaction vessel bodies used in chemical processing; large high-strength steel plates being joined to form the pressure hull of nuclear submarines; or massive subassemblies being joined to create offshore drilling platforms that serve as small cities at sea. At the other end of the size spectrum there is the joining of ever-smaller physical entities, like doped

extrinsic semiconductors being joined to create solid-state microelectronic devices; microscopic mechanical parts being assembled into micro-electro-mechanical systems (MEMS); and retinas of human eyes being reattached using lasers or cryogenic surgical probes. As with material properties, extremes pose the greatest challenges, including the added challenges of trying to join very thick or very thin sections in very large or very small structures.

As for "internal details," examples vary from geometric details (like internal stiffeners in aircraft wing carry-through structures, internal cooling passages in heat exchangers, and cell walls in expanded aluminum alloy honeycombs in lightweight structural sandwich panels) to material details (like refractory ceramic coatings on metal, steel reinforcing bars in precast and prestressed concrete, and bones, blood vessels, muscles, tendons and ligaments, and nerves in severed limbs). In fact, it is the elaborate internal details of living tissue that pose a doubly difficult challenge to joining: first, one of material compatibility or biocompatibility, and second, one of functional compatibility or functionality. For this reason (i.e., that living tissue is an inherently complex, integrated structural–material system), its joining will be addressed here, in Section 16.4.

Finally, it is not always possible to accomplish joining in the controlled environment of an automobile assembly plant, an ASME-approved pressure vessel fabrication facility, a Class 100 microelectronic clean room, or a sterile surgical suite. It is sometimes necessary to accomplish joining in a harsh environment, ranging from deep water to the fringes of outer space, from the tropical rain forests of Brazil to the frozen tundra of Siberia, or from manual welding in shipyards in Maine to remote welding in the radioactive environment of a nuclear reactor such as Chernobyl in the Ukraine.

This chapter looks at the challenges of joining structures of all kinds.

16.2 THE CHALLENGES ASSOCIATED WITH JOINING STRUCTURES

16.2.1 Joining Very Large Structures

Structures most dependent on joining for their creation are those that are very large. As stated in Chapter 1, Section 1.2, one of the main reasons joining is needed is to allow the production of structures too large to be produced by primary processing methods, including casting, molding, forging or forming, powder processing, or various special processes mostly suited to composite materials. Examples of very large structures that need to be joined for their sheer size and, often, for their geometric and/or functional complexity (calling for mixed materials) are shown in Figures 16.1, 16.2, and 16.3.

The challenge of joining very large structures is primarily the labor intensity involved, because it takes a lot of work to properly prepare the joint configurations and faying surfaces of the numerous long and/or thick joints, as well as to actually accomplish the joining. But there are also challenges posed by having to produce joints

Figure 16.1 Welding, using a variety of fusion welding, predominantly consumable electrode processes, is used almost exclusively in ship construction. Roll product (e.g., plate and beams), forgings, and castings are all welded to provide structural integrity, structural efficiency, and leak tightness. In most shipyards parts are joined to create large pre-fabricated modules, which are then joined to produce the ship, here the aircraft carrier Reagan. (Courtesy of Northrop Grumman's Newport News Shipbuilding, Newport News, VA, with permission.)

in all positions (which is especially difficult in welding, but is also a consideration in adhesive bonding as far as adhesive consistency and, thus, application methods are concerned). And such joints must usually be produced outdoors because structures are simply too big to produce indoors or off site.).

Many very large structures, such as jumbo jet airliners and the steel frameworks of skyscrapers, are mechanically fastened, the former in a plant, the latter, obviously, on site. Joining such very large structures by mechanical fastening does not pose particular problems other than the significant labor intensity in both cases. For example, a jet airliner the size of a modern Boeing 767 contains approximately 1 million rivets, each taking a laborer about two minutes to properly drill and countersink a hole, insert and set the rivet, and inspect the installed rivet. This translates to two million minutes or 33,000 labor hours! On the other hand, if very large structures to be fastened demand that very thick sections be joined, things become much more difficult (see Subsection 16.2.3).

Adhesive bonding is generally not used to join very large structures, with the important and common exception of masonry structures such as poured concrete

Figure 16.2 Welding is used extensively in the construction, erection, and service repair of large reaction vessels in petrochemical refineries, as well as many other industries. (Courtesy of Foster-Wheeler Corporation, Clinton, NJ, with permission.)

buildings, poured concrete bridges, poured concrete dams, and poured concrete highways. In all of these examples, cement is used to join one section of the structure to the next, either as individual modules or as subsequently poured sections. While one section actually chemically bonds to another through the process of hydration, various embedded reinforcements (e.g., steel reinforcing bars or meshes) or fasteners (e.g., protruding studs of various types) are also commonly used to provide a degree of mechanical interlocking (see Chapter 12, Subsection 12.2.2 and Figure 12.8). The special challenges posed by very large structures to joining in construction using cement and concrete relate to three factors: (1) curing and bonding between sequential pours; (2) bonding in all positions; and (3) dealing with the environment. When constructing a dam, for example, the sheer volume of concrete needed to produce the massive structure of the dam means that millions of cubic meters or yards of concrete will be poured over a period of many months or years, virtually nonstop. For a variety of reasons, such large concrete structures are poured in sections resembling large blocks, rather than as one continuous unit. These reasons include (1) limitations on how much wet concrete can be

Figure 16.3 Huge offshore drilling platforms, serving as self-sufficient ''cities at sea,'' use welding extensively in their land-based construction, on-site erection, and above and below water repair. (Courtesy of Materials & Welding Technology, Houston, TX, with permission.)

carried to the site in reasonable time periods; (2) the need to allow the heat of the exothermic curing/setting process to be dissipated without impeding the setting process or degrading the cured cement; (3) the need for previously poured concrete to set, to be able to support the weight of subsequently poured sections; and (4) the desirability of providing some structural damage tolerance with breaks in the elastic continuity of the inherently brittle concrete at joints. Bonding in all positions is really not too much of an issue, as cemented or mortared joints are thin and the cement or mortar tends to be held in place by surface tension forces and its own specially adjusted consistency. Controlling the size of poured sections for reasons 2 through 4, however, is critical.

By far the most common method of joining very large structures is welding. Examples of very large welded structures are ships (such as that shown in Figure 16.1), oil or gas transmission pipelines, chemical or nuclear reaction vessels (such as those shown in Figure 16.2), large pressure vessels or storage tanks, and offshore drilling platforms (like that shown in Figure 16.3). The challenges of making welds in very large structures tend to arise from two areas: (1) making welds out of position and (2) making welds outside the controlled environment of a plant (e.g., outdoors, underwater, or in outer space).

The challenge of making welds in other than a horizontal plane (with the welding heat source oriented in the so-called ''down-hand'' position) is to deal with the effects of gravity. Gravity pulls on the molten weld pool and can make it unstable. The result can be spill-out of the molten metal, resulting in gross underfill, massive voids, and highly irregular crown and root bead reinforcements. Special techniques (e.g., narrow stringer beads, weaving), special fillers (e.g., small-diameter solid wires, specially formulated coated electrodes whose slag freezes before the weld metal to hold the weld pool in place, like a mold), and special operating modes (e.g., pulsing, controlled molten-metal transfer modes) must usually be used when welding in the so-called ''out-of-position'' orientations (e.g., horizontally in a vertical plane, up or down directions in a vertical plane, or overhead).

In all welding, weld heat input should generally be kept to a minimum, for a variety of reasons, including (1) minimization of thermally induced stresses and distortion; (2) minimization of damage to base metal in the heat-affected zone; (3) creation of desirable structure and substructure in the fusion zone; and (4) control of the weld pool out of position. Hence, for welding out of position, net linear heat input should be kept even lower than usual to minimize the size and volume of the molten weld pool. This is true for shielded metal arc, flux-cored arc, and gas-metal arc welding processes. For heavy deposition processes like the submerged arc, electroslag, and electrogas, welding processes, weld pools are so voluminous that welding out of position is impossible.[1]

In addition to the effect of the basic process and heat input or power level within a process, the mode of molten metal transfer in consumable electrode arc welding processes can also have a pronounced effect on the ability to weld out of position. The preferred mode of molten metal deposition when welding with GMAW is short-circuit arc, as molten droplets are drawn directly off the tip of the melting electrode as they form by the surface tension forces of the molten weld pool whenever the droplet makes contact with the weld pool. The globular mode is usually out of the question as transfer of the large glob of molten metal would not be aided; rather, it would be hampered by the force of gravity for out-of-position welding. Spray transfer can work for some out-of-position welding by literally propelling tiny molten droplets of weld metal in the direction the electrode tip is pointing. But care must be taken to not let the heat of this inherently hot deposition mode cause too large a weld pool to develop. Pulsed-current spray of P-GMAW allows out-of-position welding because the periodic drop in current during the low-current portion of pulses allows intermittent cooling and solidification of the weld pool, so as to prevent the pool from growing to unwieldy size.

The problems associated with welding outdoors are maintaining proper shielding in high winds, keeping prepared weld joints dry during welding in rainy, snowy, or icy weather, and maintaining proper preheat or interpass temperatures to prevent undesirable untempered martensite formation in hardenable steels. The problem of shielding welds against the wind can be dealt with by using protective shelters or tents, or by using the flux-cored or "open-arc" welding process. Recall that in this process the protective gases generated by the thermal decomposition of the core fluxing ingredients must pass through the arc before being exposed to any convective currents, such as wind. Thus, by the time the protective gases can be blown away, they have done their job of shielding the molten weld metal.

Keeping the weld joint dry during welding and controlling the joint temperature are much more challenging. Again, protective shelters can be used to keep off rain or snow, and preheating can be employed using resistance-heating blankets, quartz lamps, or gas torches. Preheating also helps dry the joint before welding. Obviously, the ultimate challenge posed by the wetness and chilling effect of water occurs during underwater welding (see Subsection 16.3.1).

The final problem associated with welding very large structures is stress-relieving the joints after welding. Obviously, extremely large structures are not going to

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[1] Actually, the design of the joint and the use of moving chill plates in the electroslag and electrogas processes allow welding vertically up, but not horizontally in a vertical plane.

be placed in heat-treating furnaces. Instead of bringing the structure to the heat-treating furnace, heat treating must be brought to the structure. Localized heating using resistance heaters, quartz lamp heaters, or even gas torches is employed. Another approach is to mechanically relieve the most severe residual stresses by hammer or shot peening, planishing, or burnishing the welds, or using local mechanical vibration.[2]

16.2.2 Joining Very Small Structures or Components

At the other end of the spectrum from very large structures are very small structures or components. Joining very small components (in a process referred to as "microjoining") can cause difficulty for welding, brazing, and soldering, as well as for mechanical fastening or attachment and adhesive bonding, from several standpoints. First, and most common, is the difficulty of aligning the joint components to create the proper joint and assembly. This is predominantly a fixturing problem, but there might also be inherent problems in directing a heat source for welding, brazing, or soldering and controlling its heat input. It is often possible to attend to the alignment or fixturing problem through careful design of the joint in the first place. For example, joining of leaded or leadless electronic packages to electrically conductive pads on a substrate should allow sufficient tolerance to produce a satisfactory joint even if there is some relative misalignment during assembly. Some mechanical alignment aids, such as stops, tabs, grooves, or slots, can facilitate alignment.

Second, it can be difficult to focus the heat of a welding source on the element to be joined and nowhere else. Here, processes like laser or electron beam welding are attractive for three reasons: (1) these beams are highly focused, with high energy density; (2) they can be precisely directed or positioned by optical or electromagnetic as well as mechanical means; and (3) the energy in these beams can be precisely controlled.

The final point is that it can be difficult to control the amount of energy (i.e., the heat input) needed to cause just the right amount of melting required to form the needed and desired joint. Again, for welding, brazing, and soldering, laser or electron beam sources are attractive.

Usually for brazing or soldering microcomponents, the filler metal is preplaced on or at the joint components before attempting to apply heat. Plated or dipped coatings of the filler (often called "tinning" or "pretinning" in soldering, even though the coating may not be tin) or preforms are employed. Joints are formed by reflowing the filler by causing a general rise in the temperature of the assembly using furnaces, infrared, induction, microwave, or vapor condensation sources.

The most recent approach to the mechanical joining of microscale components in microelectromechanical systems (MEMS) is so-called "self-assembly." In self-assembly, the various components of an intended assembly are designed in such a way that they can be caused to settle together and properly align and engage simply because of their shapes,

[2] So-called "vibratory stress relief" can relieve residual stresses, but to do so, vibrations must be of high amplitude and at the resonance frequency of the structure. This can lead to more damage by fatigue than benefit by stress relief. Use of vibratory stress relief should be carefully investigated before it is embarked upon!

usually by some gentle prodding or vibration. This and other novel emerging approaches, such as "self-joining" in microelectronics, are described in a paper by Messler (2003).

Figures 16.4 and 16.5 show two examples of microjoining, with Figure 16.4 showing microjoining applied to assembly in microelectronics and Figure 16.5 showing joining in MEMS.

16.2.3 Joining Very Thick Structures or Components

Structures that consist of very thick joint elements requiring joining pose challenging problems. Almost all heavy-section joints are required to provide high load-bearing capability (and possibly high strength) and high quality and reliability, often in very demanding and even hostile environments. Examples of structures where very thick sections must be joined to result in high integrity with affordability include heavy-section armor where ballistic impact resistance is required; thick-walled pressure vessels or containers (e.g., liquid natural gas carrier tanks) where high static and dynamic loads, leak-tightness, cryogenic or elevated temperatures, and corrosion resistance are required; submarine or submersible hulls where high compressive loads, detonation impact loads, and corrosive sea water must be tolerated; and nuclear reactor components that experience high temperatures, high pressures, high static and dynamic loads, corrosive agents, and radiation. Sometimes these joints (as in submarines) must be aerodynamically or hydrodynamically smooth, or should be as lightweight as possible, as for shipboard nuclear reactors.

When joints exceed a certain thickness and structural demands become paramount, adhesive bonding is usually no longer a viable joining option. While mechanical fastening is possible and is practiced, there is a practical limit. This limit is dictated by the difficulty of preparing holes, the difficulty of installing fasteners, and, especially,

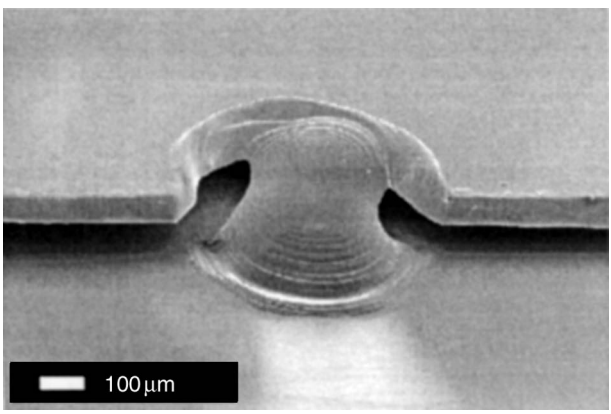

Figure 16.4 Welding is also used for microjoining for a variety of applications and industries. Here, very thin kovar sheets are spot-fillet welded by laser-beam welding to produce the minute lap joints shown. (Courtesy of Sandia National Laboratories, Albuquerque, NM, with permission.)

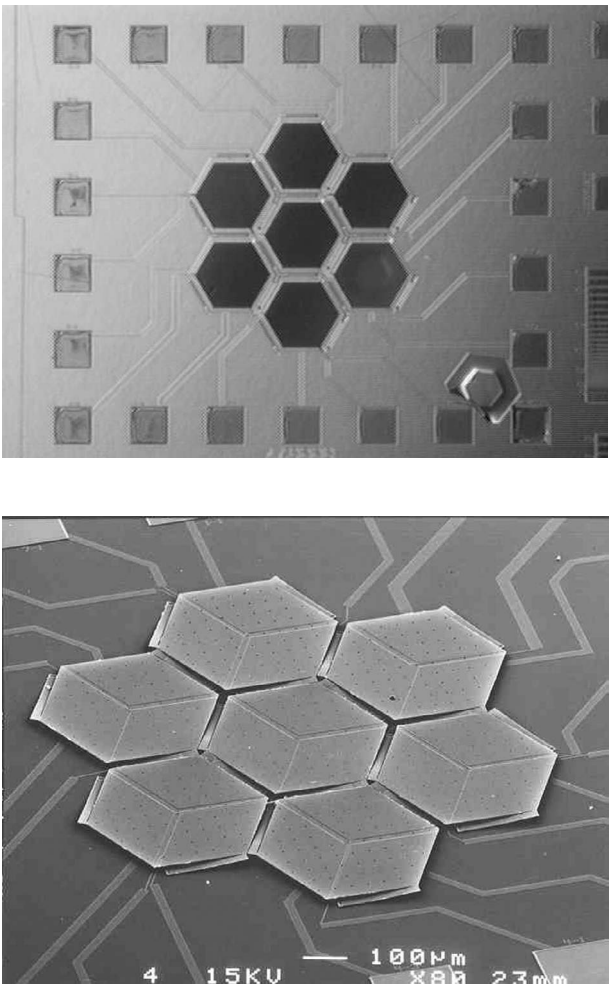

Figure 16.5 The interesting process of ''self-assembly'' is especially useful for creating MEMS devices. In the device shown here, seven tiny single crystal silicon mirrors are floated in water until they settle into the polycrystalline silicon surface-machined acutor to self-assemble. (Courtesy of the Berkeley Center & Actuator Center, University of California at Berkeley, Berkeley, CA, with permission of professor Roger Howe.)

the difficulty of developing the desired and necessary preloads or joint clamping forces. Figure 16.6 shows a steam generator composed of thick-section parts held together with specially designed and specially fabricated large bolts and nuts. For practical assembly reasons, welding is generally the only viable option for the most stringent pressure requirements and for absolute fluid tightness.

Normally, very thick sections are welded using many passes applied by heavy-deposition fusion welding processes, such as (in approximate ascending order of

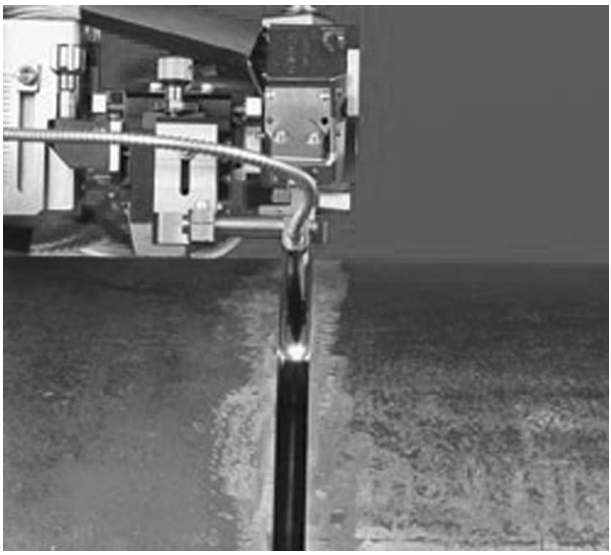

Figure 16.6 An example of welding being applied to a very thick section joint. Here mechanized narrow-gap of narrow-groove gas metal arc welding is being used to fabricate nuclear power plant reactor components. (Courtesy of EPRI, the Electric Power Research Institute, Charlotte, NC, with permission.)

deposition rate capability) gas-metal arc welding (GMAW), submerged arc welding (SAW), and electrogas or electroslag welding (EGW or ESW). Other options are GTAW employing very high current (several thousand amperes), hot-wire GTAW (HWGTAW), or various so-called "narrow gap" welding processes, such as a multi-wire variant of the GMAW process. Joints for such processes are usually prepared with wide openings to provide good access for the welder. Single V, U, or J or double V, U, or J preparations are common. Figure 16.7 schematically illustrates joint designs for thick-section welded assemblies.

While multipass, heavy-deposition-rate welding processes can produce some welds, the total amount of filler metal required and the tremendous total heat input used lead to significant shrinkage in the weld metal, and distortion and/or residual stresses in the joint. In addition, the skill level required of manual welders or weld operators who operate automated welding systems, the labor intensity, and the overall cost are usually high and may be prohibitive. Furthermore, nondestructive evaluation can be quite challenging and repair can be extremely difficult and costly. Finally, multiple passes result in overlapping HAZs, which can greatly complicate and compound the effects on the microstructure in these regions.

To minimize the problems associated with the large mass or volume of weld metal in a multipass weld, welding procedures must be thoughtfully developed and carefully controlled. Welds need to be sequenced to balance heat input. Alternating passes must often be made from opposite sides of the joint to offset any shrinkage, and not all passes should be made in one joint until it is finished. Rather, a pass should be

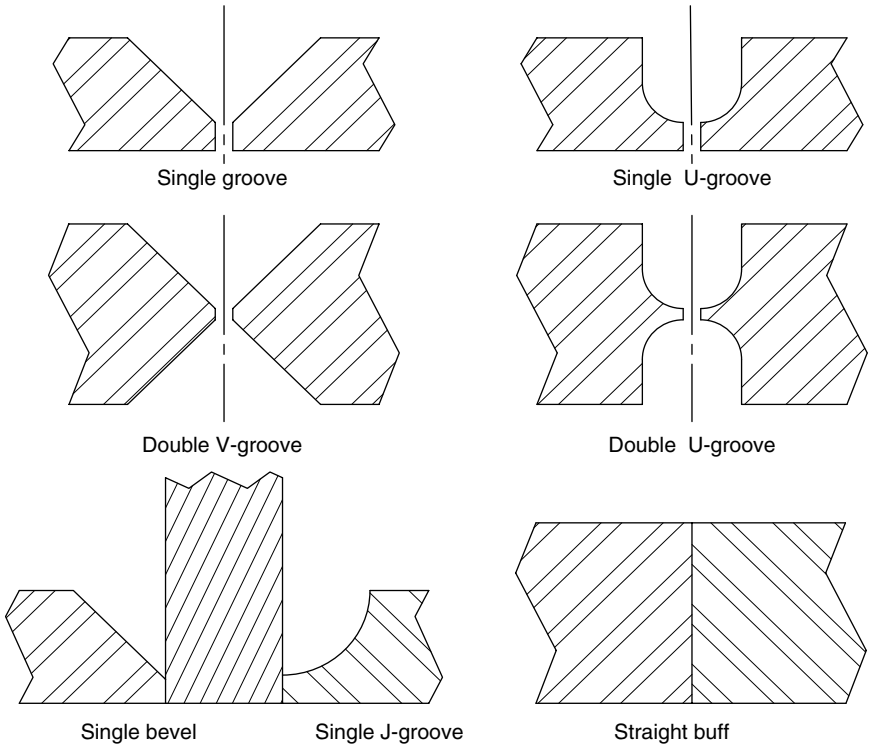

Figure 16.7 Schematic illustrations of typical thick-section joint options for welding, including single V- and U-grooves (top row), double V- and U-grooves (middle row), and single-bevel and single-J grooves (bottom row, left) and straight or square butt joint (bottom row, right).

made in one joint and then in another somewhere else on the weldment to offset any possible distortion. In hardenable alloys, each pass can be used to temper previous passes to some degree, and subsequent passes always provide some stress relief in previous passes. Finally, overall temperature (i.e., ''interpass temperature'') should be controlled to prevent metallurgical degradation and distortion or residual stresses.

An attractive alternative to multipass welding is to use a fusion-welding process that is capable of producing deep penetration welds in single, or at least fewer, passes. Candidate processes must be capable of producing welds with very large depth-to-width ratios. Example processes are electron beam, high-power laser beam, and certain narrow-gap processes. Narrow, single-pass welds can be produced by these processes as follows:

- Up to 10–55 cm (4–6 in.) in steel or titanium, or 25–35 cm (10–14 in.) in aluminum by EBW with 100 KVA systems
- Up to 7.5–12.5 cm (3–5 in.) by narrow-gap processes in steel- or nickel-base alloys
- Up to 5 cm (2 in.) by high power (e.g., over 10 kW) LBW in certain metals with low reflectivity (like steels)

For the most part, these processes (i.e., EBW and LBW) have very high energy density heat sources (greater than 10^9 watts per square centimeter), and, thus, operate in a keyhole mode. The result is deep penetration, minimal weld fusion zone width, minimal volumetric shrinkage, minimal distortion, high welding speeds, low net linear heat input, minimal heat effect and HAZ width, and minimal residual stresses. Also, complications from overlapping HAZs are avoided. An example where single-pass EB welding enabled precision assembly without distortion was in the F14 fighter aircraft's all Ti–6Al–4V wing carry-through structure. This 22-foot-long, 4-foot-wide, 1.5-foot-deep box assembly was entirely EB welded, using single-pass welds varying in depth from approximately one inch to over two inches. EB welding enabled more than 300 pounds to be saved over mechanical fastening and allowed a tolerance of $+/-0.020$ in. to be held between the centers of pivots at each end of the 22-foot-long box. Welded joints were designed to demanding fatigue and fracture toughness criteria because of the criticality of this "backbone" of the aircraft.

Usually these single-pass, deep penetration welding processes require fairly precise fitup between abutting joint components to help reduce shrinkage and distortion. Square- or straight-butt preparations are common (see Figure 16.7f), and welding is usually done autogenously (i.e., no filler metal is used) because of the difficulties of getting the filler down into the deep, narrow weld. Resulting welds are usually fairly parallel sided, so the heat distribution through the thickness is fairly uniform. This further reduces the distortion typically found with taper sided, multipass welds.

Because the level of residual stresses that can develop can be very high in thick sections, special care must be given to relieving these stresses after welding. Thermal treatments (i.e., stress relief annealing) are preferred, but the size of the weldment and the location of the site where welding occurs (e.g., on site versus in plant) often make such treatment difficult or impractical. Localized stress relief is often practiced through the use of high-intensity quartz lamps, resistance-heated blankets, gas torches, etc. If thermal stress relief is impossible, welding procedures should be carefully selected and performed to minimize residual stress development, and vibration or vibratory stress relief or post-weld mechanical treatment by peening or other means should be attempted.

16.2.4 Joining Very Thin Structures or Components

Very thin structures or components are composed of very thin materials, so joining must be done carefully to avoid any concentration of loading and resultant stress that could cause failure by buckling under compression, tear-out at edges due to bearing, or pull-through of fasteners or weld beads due to tension or peel. Obviously, thin sections are also quite susceptible to heat damage, either by overheating to cause melting or "burn-through" or by distortion that is severe enough to prevent proper fit and/or function. Some examples of where thin material elements must be joined are (1) thin formed diaphragms to heavier-section support frames or housings (e.g., in hermetically sealed pressure, vacuum, or environmental systems); (2) thin formed flexible bellows to one another or to end fittings or housings (e.g., in fluid ducting or vacuum systems); (3) expanded honeycomb cores to create honeycomb cores proper or to attach cores to face

sheets to produce sandwich panels for structural or thermal applications; and (4) seams in thin metal, polymer, or reinforced thin sheet stock (e.g., as in the making of metal cans, metal heating and air conditioning ducts, sheets of plastic as used in balloons, etc.). The basic process options for joining thin materials and material structural elements include, in decreasing order of popularity (if not suitability), adhesive bonding, brazing or soldering, welding, and, to a limited extent, mechanical fastening or integral attachment.

If adhesives can be used to bond thin sections of materials together or to thick sections of materials (as discussed in Subsection 16.2.5), they should often be the choice. In fact, adhesive bonding is widely used in the joining of thin sections, as exemplified by adhesively bonded plies in laid up or laminated composites, or in adhesively bonded honeycomb panels. If the service environment is hostile to adhesives because of elevated temperatures, moisture, solvents, or biological agents, brazing or soldering would be logical joining alternatives, as these processes also spread loading when large surfaces are joined face to face. Mechanical fastening and integral mechanical attachment are fundamentally more difficult because the thin sections are unable to tolerate bearing or fastener tear-out or pull-through loads and stresses. However, fastening using stitching, sewing, or stapling is possible, as is integral attachment using special techniques analogous to Tog-L-Locs (see Chapter 3, Subsection 3.5.5).

The key to joining very thin sections by welding is keeping the temperature of the joint as low as possible and minimizing the net linear heat input by welding at very high speeds with any fusion welding process, or using high energy density processes at extremely high welding speeds. Great care must be taken to concentrate the heat from the welding heat source on the specific area to be joined, minimizing the exposure of surrounding areas to potentially damaging heat to prevent metallurgical degradation or distortion, but without concentrating the heat so much that overheating or burn-through occurs. This involves delicately balancing heat input.

Soldering is obviously the preferred choice over welding and even brazing, because of its requirements for melting only the filler and not approaching the melting point of most metal substrates (provided the solder's strength is sufficient). For very thin sections, with sufficient overlap, joint strength can easily be considered structurally as well as hermetically tight. In addition, proper joint design can enhance the joint's strength (see Chapter 8, Subsection 8.2.1).

For more demanding structural applications, brazing is the next best choice. Here, however, the entire structure is normally heated to just below its solidus temperature and the filler alloy is melted to create the joint by capillary flow. Once again, the preferred joint configuration is a lap, either single-overlap or spliced double-overlap. Rarely would a gas torch be used because of the risk of rapidly overheating the joint area accidentally. Gentler heating processes such as induction or infrared, or more directed processes like resistance, tend to be preferred. Structural metal honeycomb, such as titanium honeycomb widely used in aerospace applications, is usually produced by brazing stacked-up thin sheet- or foil-gauge plies along specific lines and expanding the brazed stackup to produce the honeycomb, much as corrugated cardboard is produced by gluing plies of paper and expanding that stackup. Brazing is also commonly used to join facing sheets on honeycomb core sandwich panels, with the brazing alloy often being plated or otherwise precoated to the sheets or foils.

Fusion welding can be used to join very thin sections, provided (1) the heat input is kept to a minimum to cause just the amount of melting that is needed; (2) the source is precisely located; and (3) the energy from the source is properly concentrated only over the area to be joined. Preferred processes for welding very thin sections include: laser beam and electron beam for precise control of energy input and position and to minimize heat input through high welding speeds; gas–tungsten arc and plasma arc using very small torches, small-diameter non-consumable electrodes, and very low currents (e.g., less than a few amperes) called "needle arcs"; and resistance spot or seam, or ultrasonic friction welding. Resistance welding minimizes heat input by heating very rapidly, while ultrasonic friction welding avoids melting altogether. Diffusion welding and diffusion brazing are viable options for producing sound joints in appropriate materials (e.g., Ti, Ni, and Cu and their alloys).

16.2.5 Joining Thin to Thick Components

For those special cases where very thin-section components are to be joined to thicker-section components, special care must be exercised to properly distribute or balance the heat input to each portion of the joint. The tendency, of course, is to overheat the thin section while trying to overcome the conduction of heat away from the joint by the heavier thermal mass, which acts like a heat sink. Techniques that can help are: preheating the heavier joint element to reduce the heat needed from the welding, brazing, or soldering source to raise it, or its filler, to the melting point and/or applying cooling in the form of moistened pads, heat-blocking compounds, or copper chill blocks to the thin section to extract excess heat and prevent unwanted heat spreading. Similar techniques of "heat damming" are used to protect heat-sensitive (e.g., flammable) materials in the vicinity of a joint to be welded. Figure 16.8 schematically illustrates typical thick-to-thin joints as well as examples of joints in some heat-sensitive structures and environments.

16.3 THE CHALLENGES OF JOINING IN HOSTILE ENVIRONMENTS

Because hostile environments, by their nature, almost inevitably place great demands on a structure, the joints and the joining processes used to produce those joints must be carefully selected and performed. Knowing a structure will have to survive in the highly corrosive, high-pressure environment found under the sea, for example, places additional demands on the materials selected for and the joints used in a structure for this environment. The same is true for the proper and safe functioning of a structure in outer space or for use in the high radiation flux of a nuclear reactor. But beyond having to *function* in hostile environments, sometimes joining has to be *performed* in hostile environments. This is, obviously, another of those "extremes" that challenge joining.

Hostile environments in which joining needs to be performed are many and varied, and probably are more widespread than one might think. Hostile environments might mean hostile to the mechanic or welder or other worker, thus requiring that

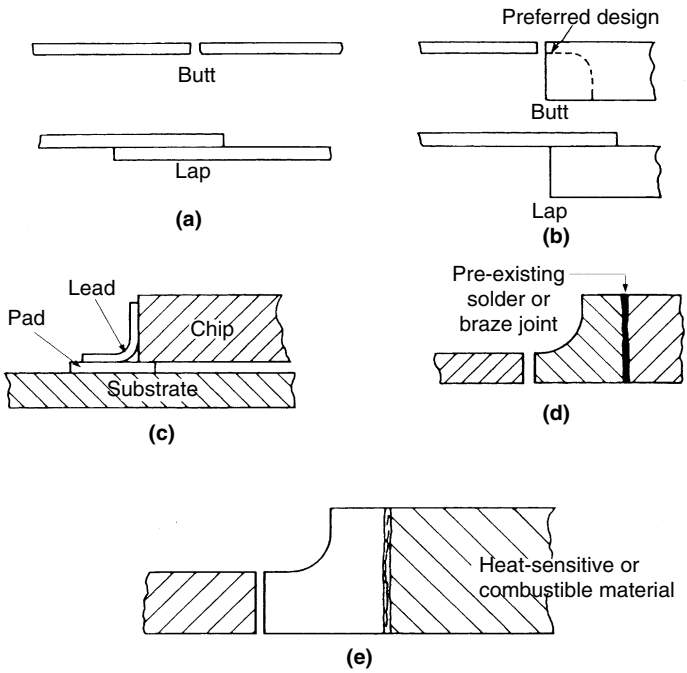

Figure 16.8 Schematic illustrations of butt and lap joints for thin sections (upper left), as well as for thin-to-thick joints (upper right), along with some special joints designed to allow thin-to-thick sections to be joined without problems from the thicker section pulling heat from the joint (middle row), as well as to allow welding near heat-sensitive materials (bottom row).

joining be automated and often remote or it might mean hostile to the joining process or the joint proper. And, of course, there is hostile, and there is really hostile! Welding steam mains under the streets of Manhattan is hostile by many people's standards and certainly as compared to controlled manufacturing environment standards. But such joining is routine and is performed every day in every large city on this planet. Bolting or riveting steel structures for a skyscraper, or welding on the cable-supporting tower of a suspension bridge, are hostile environments for most people. But, again, such joining is routine for steelworkers. Welding ships in yards from the cold, snowy, and icy coast of Maine to the steamy Gulf coast of Texas is a hostile environment by many standards (due to moisture, humidity, cleanliness, wind and wind chill, etc.) Natural resources like oil and natural gas must be extracted where they occur, and these places are often hostile—consider the scorching sands of the deserts of the Middle East, under the permafrost of the Alaskan wilderness or the steppes of Russia and Siberia, or under the ocean from the tropical Gulf of Mexico to the fierce North Sea. The tundras of North America or Siberia are hostile to welding oil and natural gas drilling rigs and transmission lines. But the most hostile environments of all are in the depths of the oceans, at the fringes of outer space, and in the radioactive environment of nuclear reactors.

16.3.1 Joining in Extreme Cold

Oil and natural gas deposits are often found in inhospitable areas of the globe, most notably in the near-Arctic regions of North America—the upper regions of Canada and Alaska and in the northern reaches of Siberia. In all of these places, temperatures plummet to −70°C (−90°F) and below in the dead of long winters, and ever-present wind chills make these ferocious temperatures even worse. The most practical, economical, and environmentally benign method of moving oil and natural gas from their point of recovery to their point of use is by pipeline. There are more than one million miles of such pipelines in North America and more than twice that number in the Russian Federation, which includes Russia and Siberia. There are hundreds of thousands more miles of pipeline in Asia Minor and the Middle East. These pipelines are made of hardenable steel and range in diameter to nearly two meters (over six feet). Prefabricated sections must be circumferentially welded to produce joints that are, obviously, leaktight, "x-ray clean" (i.e., defect-free), and free of severe residual stresses and untempered martensite in the fusion zone (FZ) and heat-affected zone (HAZ). Because the natural gas, at least, is under positive pressure, these pipelines must meet pressure vessel codes. This demands careful welding to stringent, prequalified procedures by certified welders in all positions (as most of the circumferential weld is "out of position" and, obviously, in place (on site)).

Untempered martensite can form when post-weld cooling exceeds the critical cooling rate for the steel, which is especially likely in cold steel in which steep temperature gradients exist. To prevent this, preheat must be applied at the start of welding, a minimum interpass temperature must be maintained throughout welding, and thermal stress relief must be applied either during or after welding. Preheating can be accomplished using resistance-heated blankets or by locally applying the flame of a gas torch or array of torches. While always challenging, this can be especially difficult to achieve in severe cold weather conditions. Likewise, proper shielding can be more challenging due to wind. Interpass temperature can be controlled using temperature-indicating waxes that melt at predetermined temperatures (e.g., TempilStix). Stress relief can be accomplished using resistance-heated blankets, locally applied gas torches, or a technique known as "temper beads." Here, subsequent stringer beads in a multipass weld are used to partially stress relieve as well as temper any untempered martensite created in or by prior underlying passes.

Figure 16.9 shows pipeline welding in progress in a hostile desert environment.

16.3.2 Joining Underwater

The ever-increasing erection of larger and larger offshore drilling platforms in deeper and deeper water, as well as the need for scheduled maintenance and unscheduled repair of nuclear reactors in power generating plants, is increasing the need for joining underwater. While mechanical fastening, using bolts and nuts (at least for offshore drilling platforms) is performed, the presence of stresses from necessary bolt preloading can lead to stress corrosion failures in many susceptible alloys. Adhesive bonding,

Figure 16.9 Welding is used to construct overland pipelines in all kinds of climates, including frozen tundra or scorching deserts, as shown here. (Courtesy of Bechtel Corporation, San Francisco, CA, with permission.)

other than using special grades of cement for large cement or concrete underwater structures, is rare, although use of polymeric adhesives applied "topside" for underwater service is not unusual. The challenges of underwater welding include (1) the obvious problem of removing and excluding water from the welding envelope to prevent hydrogen embrittlement in susceptible steels when the water dissociates in an electric welding arc; (2) the less obvious (but understandable) problem of extreme pressure on arc action and the forcing of gases into the molten weld pool (in accordance with Sievert's Law); (3) the potential problem that rapid cooling by wet, especially cold, water can cause; (4) the safety hazard posed to human welders by the electricity in arc welding; and (5) the frequent need to accomplish welding remotely because of the risk to humans. Specially formulated welding consumables (e.g., coated SMAW electrodes and flux-cored wire electrodes) and specially developed welding procedures have been developed for welding underwater, but much more work needs to be done with increasing demands of depth and usage.

Figure 16.10 shows welding being performed underwater.

16.3.3 Joining in a Radioactive Environment

The challenge of joining, and most frequently welding, in a highly radioactive area is primarily associated with the need for all operations to be performed remotely with robots, with the added problems associated with having to prepare joints (at least during repairs or maintenance) remotely and automatically. The use of most polymeric adhesives is precluded by the severe degradation of many polymers by high radiation fluxes, while the use of mechanical fastening is largely precluded by the difficulties associated with preparing fastener holes and installing fasteners remotely. Regardless of what process was used to produce joints in such a structure when it was first built, repair becomes much more difficult if the use of automation, including remotely operated systems, was not planned from the outset.

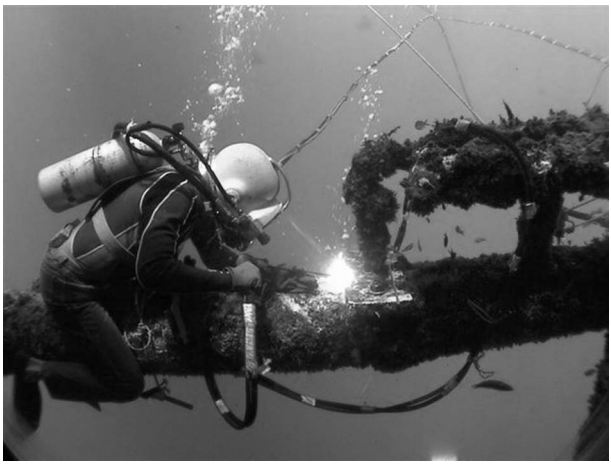

Figure 16.10 Underwater arc welding is necessary for both construction and repair. Here, a diver is shown arc-repair welding an obviously overgrown steel structure. (Courtesy of Dave's Diving & Offshore, in memory of Chris Mourtinson, Morgan City, LA, with permission of David Gilbert.)

16.3.4 Joining in Outer Space

Humankind has been venturing into outer space and spending longer and longer periods of time there to perform more and more sophisticated research for more than three decades now. This has culminated in the present International Orbiting Space Station, which was erected by joining "on site." Space is a hostile environment due to the hazards of vacuum and the usual annoyance of weightlessness. Virtually all polymer adhesives will outgas in the severe vacuum of space (estimated at 10^{-14} Torr!). Mechanical fastening is possible, and the use of integral mechanical attachment is—or ought to be—particularly appealing. The challenges of welding in space are fourfold. First, the total absence of air (i.e., the presence of a severe vacuum) is at once a blessing for shielding and a severe limiting factor for process selection. Arc welding is extremely difficult due to the scarcity of gas atoms to ionize and create an arc. Even if an arc can be formed, it is inherently unstable and difficult to control. Electron beam and laser beam welding, on the other hand, become very attractive, and both have been used. Second (and related to the presence of a vacuum), evaporative loss of high vapor pressure solutes and even solvents could pose severe problems in achieving desired compositions and weld density because outgassing produces porosity in the fusion zone. Third, the absence of gravity can make molten metal transfer and the precise placement of weld metal difficult. Fourth (and common to all hostile environments), manual welding becomes difficult, impractical, or impossible. Thus, welding must be done automatically and, usually, remotely using robotic systems equipped with elaborate sensors or using human-operated telemanipulators.

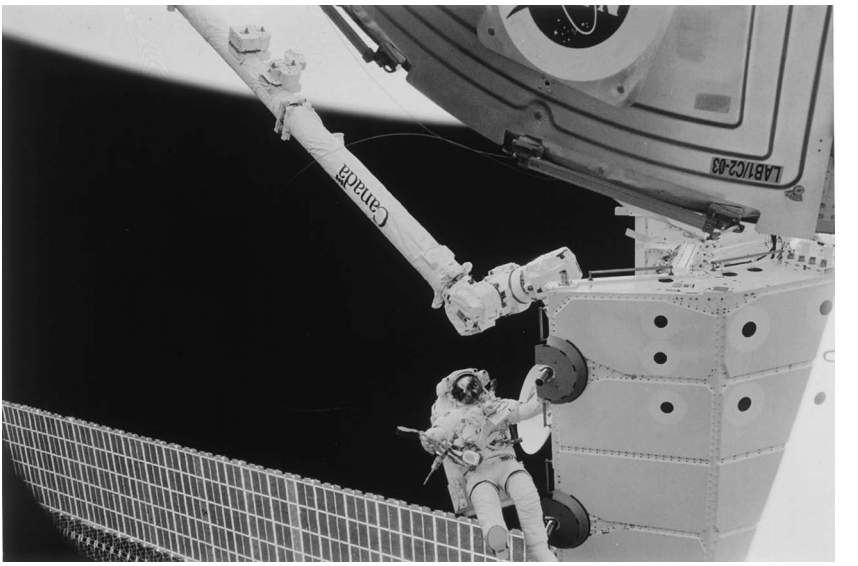

Figure 16.11 As humans venture farther and stay longer in outer space, joining by specially adapted conventional processes as well as yet-to-be-developed processes will be a necessity. Here, an astronaut assembles new parts onto a portion of the International Orbiting Space Station. (Courtesy of the National Aeronautics and Space Administration, Washington, DC, with permission.)

Figure 16.11 shows how astronauts are required to join large components fabricated on Earth while in outer space during extra-vehicular space walks. Such necessities will demand new methods for joining in such a harsh and hostile environment.

16.4 JOINING LIVING TISSUE

16.4.1 Living Tissue as a Structure as Opposed to as a Material

Surely the most complex and elegant material of all is living human tissue. In fact, living tissues[3] are essentially composite structures more than they are materials. They consist of a framework of "scaffold proteins" (i.e., an *extracellular matrix*) populated with living cells, with water, ions, lipids, and other components also incorporated. When either trauma or surgery causes a tissue wound to have to heal, or the transplantation of living tissue or organs or the implantation of nonliving material components to have to be integrated into the body, it is joining that is really occurring.

When joining of tissue is to occur, both the living and nonliving components must be taken into account and dealt with. When nonliving material components (e.g., bone repair hardware, synthetic heart valves, artificial hip joints, etc.) are to be

[3] *Tissues* are defined as "aggregates of morphologically and functionally similar cells." Hence, there are many different tissues in the human body, each designed (by evolution) for a specific purpose in the body.

Table 16.1 List of Biocompatible Materials for Implantation And Their Key Properties

Material	*Young's Modulus (GPa)*	*Yield Strength (MPa)*	*Tensile Strength (MPa)*	*Compressive Strength (MPa)*	*Fatigue Strength (MPa)*	*Elongation (Annealed) (%)*
Cortical Bone:	15–30	30–70	70–105	–	–	–
Metallic Materials:						
Stainless steel (316L)	190	221–1213	586–1351	–	241–820	40
Co-Cr-Mo	210–253	448–1606	655–1896	–	207–950	20–50
CP Ti (Grade 4)	110	485	760	–	300	30
Ti-6Al-4V	116	896–1034	965–1103	–	620	25
Ceramic Materials:						
Alumina	380	–	350	4500	–	–
Bioglass-ceramics	22	–	56–83	500	–	–
Calcium phosphate	40–117	–	69–193	510–896	–	–
Pyrolytic carbon graphite	18–28	–	280–560	517	–	–
Polymer Materials:						
PMMA	2.2	–	30	–	–	1.4
Nylon 6.6	2.8	–	76	–	–	90
PET	2.1	–	53	–	–	300
Poly(lactic acid)	1.2–3.0	–	28–50	–	–	2–6
Polypropylene	1.1–1.6	–	28–36	–	–	400–900
Polytetrafluoroethylene	0.5	–	17–28	–	–	120–350
Silicone rubber	1–10	–	2–8	–	–	160
UHMW Polyethylene	4–12	–	<35	–	–	<300

joined, "biocompatibility" must be taken into account and achieved. Materials that constitute parts of medical implants, extracorporeal (outside the body) devices, and disposables that are used in medicine, surgery, dentistry, and veterinary medicine, as well as in every aspect of patient health care, are referred to as "biomaterials." Metallics, ceramics, glass, polymerics, and a variety of composite materials have been used as biomaterials; examples and key properties are shown in Table 16.1. It should come as no surprise from the repeated statements made throughout this book that selection of a specific biomaterial—like all materials—for a particular application must be based on physicochemical properties and property compatibility, mechanical properties and property compatibility (e.g., tensile and compressive strength, stiffness, fatigue endurance, wear resistance, and dimensional stability), as well as durability for the intended service. However, biocompatibility is the paramount criterion that must be met by a biomaterial.

16.4.2 Living Tissue Repair Versus Implantation of Nonliving Materials

The interactions of tissue and body fluids with biomaterials or medical devices is an area of crucial importance to all kinds of medical technologies, must notably, for the

purposes of this book, joining of tissue. Joining of living tissue is a challenge in two ways. The first and oldest way, in one sense, is the joining associated with the implantation of nonliving materials, including (1) metallic bone fracture fixation wires, pins, screws, nails, and plates; (2) metallic vascular stents; (3) metallic or polymeric artificial heart valves; (4) metallic, ceramic, or polymeric reconstructive medical implants (e.g., metallic hip prostheses, ceramic middle ear implants, polymeric cartilage replacements); and (5) polymeric interocular lenses. For such joining, the crucial consideration is a compatible tissue–implant interface, for it is at this interface that atomic-, molecular- and cellular-level events occur that determine success or failure in joining (see Figure 16.12). The interface between the implanted biomaterial and the body involves a complex and challenging biological environment (see Figure 16.13).

The second method, far more recent and exciting, is the joining of living tissue to other tissue in what has been known as tissue grafting (e.g., of skin or bone) and organ transplantation. This is evolving into what is being referred to as "tissue engineering." *Tissue engineering* was defined in a late 1980s National Science Foundation (NSF) workshop as: "The application of principles and methods of engineering and life sciences toward the fundamental understanding of the structure-functional relationship in normal and pathological mammalian tissues and the development of biological substitutes to restore, maintain, or improve functions." While the joining of natural

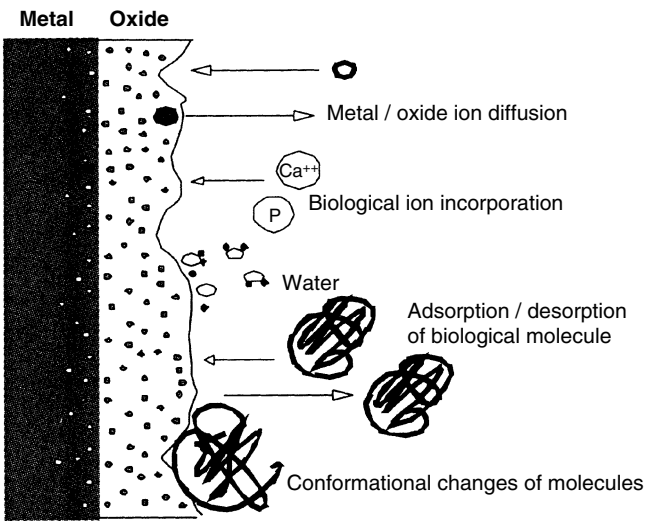

Figure 16.12 Schematic illustration of the atomic- and molecular-level events at the surface of a metal implant. On a macroscopic level, the surface of a metal implant may appear to be smooth, uniform, and inert. On the microscopic level, such a surface probably varies in chemical composition and topology and is the location of a number of dynamic molecule-surface interactions. (Reprinted from *An Introduction to Tissue-Biomaterial Interactions*, by K.C. Dee, D.A. Puleo, and R. Bizios, Wiley-Liss, New York, NY, Fig. 0.1, page xviii, 2002, with permission of John Wiley & Sons, Inc., Hoboken, NJ.)

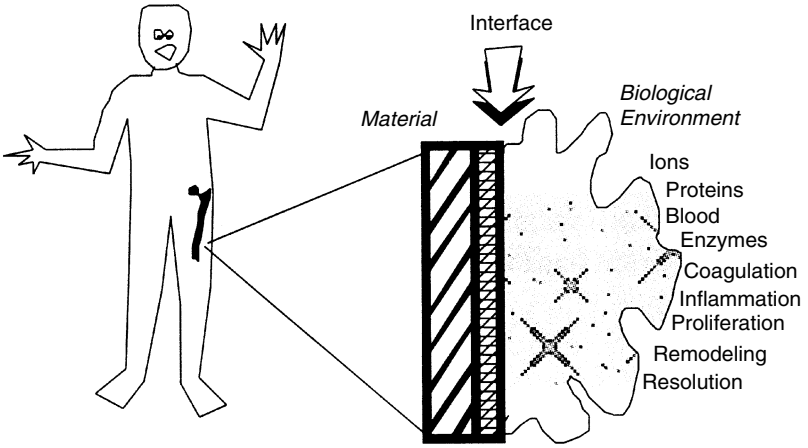

Figure 16.13 The interface between a biomaterial and the body, using a hip implant as an example. Whereas the bulk material is metallic (titanium, for example) the surface of the implant is probably comprised of an oxide layer (e.g., titanium oxide). The interface between this surface oxide and the biological environment is the location for ions, proteins, enzymes, and other biomolecules to interact with the biomaterial, as well as the location where stages of the body's wound healing process will occur. (Reprinted from *An Introduction to Tissue-Biomaterial Interactions*, by K.C. Dee, D.A. Puleo, and R. Bizios, Wiley-Liss, New York, NY, Fig. 0.3, page xix, 2002, with permission of John Wiley & Sons, Inc., Hoboken, NJ.)

tissue as in a surgical procedure (e.g., using suturing or a fibrin sealant/adhesive) is probably not within this definition, such joining is still obviously important.

Generally, there are four fundamental types of tissue: (1) connective, (2) epithelial (which occurs in sheets, like skin), (3) muscle, and (4) nervous. Tissues are also classified as "hard" (bone) or "soft" (pretty much everything else, including cartilage). Together, these are analogous to the classification of materials as metals (which tend to be strong and ductile), ceramics (which tend to be strong and brittle), and polymers (which tend to be weak and viscoelastic). Most tissue is "vascularized" (i.e., fed by blood) to some degree, with cartilage being an exception in that it is poorly vascularized.

As stated earlier, most, if not all, tissues are composite structures. The living cellular component provides many of the tissue-specific functions, and the protein matrix has important structural roles as well as functional significance. The living cells in the tissue generally secrete and remodel the matrix around them, as in wound healing, to create an environment that suits them and promotes their required functions.

The key to joining living tissue to other living tissue, to tissue engineered *in vitro* (i.e., outside the body, in a "test tube"), or even to nonliving materials is wound healing. Wound healing, which is the natural response to tissue damage from injury or surgery, is a remarkable testament to the body's capacity to regenerate cells characteristic and pertinent to specific tissues and organs, to replace connective tissue

and blood vessels, and, thus, to repair damage through the process of joining. While the detailed mechanisms at the atomic or molecular level are not fully understood, it is known that the process is triggered by injury to the tissue and/or by the presence of synthetic biomaterials, and that is follows a series of fundamental stages. These are shown in Figure 16.14 as injury ⇒ coagulation (of blood) ⇒ inflammation (which is simply the natural process of initiating repair, not an infection!) ⇒ repair and remodeling.

It is interesting and fortunate (in fact, essential) that this joining-based process is self-initiated in living tissue, but this is, in fact, not unique to living tissue. "Self-joining" and "self-limiting joining" are made to occur in microelectronic assembly, as when an Al- or Mg-containing alloy (say of Cu) is placed in intimate contact with an oxidized Si substrate (e.g., a wafer) and is heated to allow the thermodynamically driven formation of an Al_2O_3 or MgO bonding interlayer. "Self-healing" materials are enabled by, for example, nanotechnology when inert material-encapsulated catalysts and uncured resin are embedded in the cured resin matrix of a thermosetting polymer-matrix composite. When the shells of the embedded nanoscale capsules are broken by a propagating crack, the released resin and catalyst react to heal the crack. Of course, these are not living materials, but, even in living tissue, processes like healing are triggered at the atomic, molecular, or cellular level by chemical or electrical or mechanical stimuli and chemical processes.

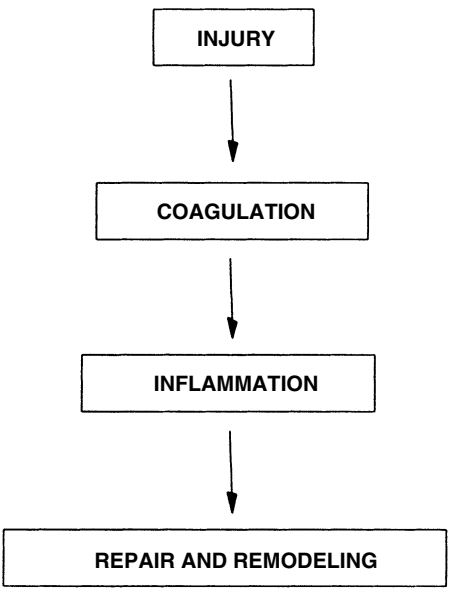

Figure 16.14 Fundamental stages of the wound healing process in the body. (Reprinted from *An Introduction to Tissue-Biomaterial Interactions*, by K.C. Dee, D.A. Puleo, and R. Bizios, Wiley-Liss, New York, NY, Fig. 0.2, page xix, 2002, with permission of John Wiley & Sons, Inc., Hoboken, NJ.)

16.4.3 Fundamentals of Joining or Regeneration of Tissue

The unsurprising, if not obvious, fundamental challenge associated with joining living tissue, any time, is to keep everything about the process very close to physiological conditions. In humans, this includes full hydration (adequate water); temperature close to 37°C (98.6°F); pH $\sim$ 7.4; appropriate partial pressure of O_2; ionic strength; and some others. All of these factors must be maintained to ensure that the living cells in a tissue do not die. These living cells also preclude the use of toxic chemicals in the joining process.

To allow living tissues to join to nonliving materials, the nonliving materials must be biocompatible (see Subsection 16.4.1). For implanting or transplanting living tissue, there must also be compatibility in terms of matching key biological factors to preclude rejection by the body's immune system.

When considering the joining of living tissue to living tissue, the cellular component and the nonliving component (mostly protein scaffold matrix) must be joined to themselves and each other. However, the key is really to consider the living cellular component because, ideally (if implantation or transplantation is done correctly) the living cells will do the joining themselves (i.e., cause wound healing). The cells adhere to the protein scaffold around them via specific sets of receptors (called "integrins") that provide a link between the outside of the cell and the inside of the cell. Cells need an appropriate matrix to attach to, and this can be challenging since cells can sense (from chemical, electrical, and mechanical stimuli) their surroundings and will not attach to just anything.[4]

In fact, since most of the nonliving component of tissue consists of protein (often fibrous protein[5]) that has been secreted and remodeled by the cells, it is the cells that also repair (i.e., join) the protein scaffold as an early step in wound healing. Proteins have difficulty joining to themselves or being joined without the help of the cells.

As composites of living cells in a "scaffold" of proteins called the extracellular matrix (ECM), tissues are critically dependent on such protein scaffolds for a variety of reasons. First and foremost, they provide the primary structure of a tissue and provide most of the mechanical strength. The scaffold proteins are also important in regulating cell function by signaling the cells in a tissue and changing that signal when conditions change (e.g., when the tissue is injured). Cells need the protein scaffold so they can migrate through a tissue by attaching to and moving along the scaffold protein like a spider on a web. The cells are also able to remodel the scaffold in order to suit their needs if conditions change.

In the body, the protein scaffold is produced by living cells from materials that these cells secrete. In tissue engineering (within which one could include joining as a

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[4] This is almost certainly part of the "grand design" of the human system to ensure that inappropriate cell growth does not occur (i.e., without attachment or irrespective of the matrix).

[5] In fact, the proteins comprising the matrix of different tissues in the body are of different types, each with its own particular characteristics. Major examples include collagen (important as a structural framework in bone, skin, and blood vessels); elastin (important for its inherent elasticity in skin, blood vessels, ligaments, and lungs); fibronectin (important for organizing the matrix and allowing cells to attach to it); and fibrinogen (critical to blood clotting and other physiological and pathological processes).

necessary component for success), there are a variety of approaches for creating a scaffold on which implanted and/or new tissue can grow, roughly divided, as follows:

Synthetic Polymer Scaffolds. In this case, synthetic polymers are created as scaffolds for cell attachment. These polymers may be permanent or may be biodegradable, with the idea that the cells will replace the degrading polymer with new natural tissue (protein). Often, as will be discussed in Subsection 16.4.4, the polymer needs to be treated in order to get cells to adhere to it satisfactorily. Common polymers in this class include poly(lactic acid), poly(glycolic acid), and other poly-anhydrides.

Naturally Derived Polymers. In this approach, the cells are provided with a scaffold that has been taken from nature (often from the body). These are generally large proteins and may be supplied to the cells in a solubilized form to be reconstituted into the solid form by the cells, or they may be decellularized tissues that are then repopulated with living cells. Examples of this approach are the use of collagen and fibrin as scaffold proteins.

Cell-Secreted Scaffolds. In this case, the cells are encouraged to produce their own scaffold by being stimulated biochemically and/or mechanically. This has the advantage that the cells do all the work and, theoretically, lay down the right matrix for themselves to be comfortable. In practice, it is difficult to get cells to lay down enough matrix and for it to be laid down in the form required to allow production of new tissue.

There is, obviously, much more to this than is known, and even more that is not yet known. The interested reader is referred to some of the references in the bibliography at the end of this chapter, and to the ever-evolving literature.

16.4.4 Methods for Joining Living Tissue

Not surprisingly, current approaches for joining or rejoining living tissue to other living tissue or to nonliving materials (e.g., material implants) can be divided into mechanical joining, adhesive bonding, and welding, at least by an analogue. As in the joining of nonliving metals, ceramics, glasses, and polymers, these fundamental joining processes rely, in turn, on fundamental forces that are mechanical, chemical, and physical in nature.

Mechanical Joining of Living Tissue. Suturing (analogous to sewing and stitching), stapling, and wiring are, of course, well known soft tissue joining techniques. They rely on unthreaded fasteners (i.e., supplemental devices) to stabilize soft tissue (e.g., muscles, ligaments, tendons, blood vessels, and skin) so that the living cells of these tissues can heal the wound. Wound closure by suturing extends back many centuries. There is also broad use of screws, nails, pins, splice plates, etc., mainly in orthopedic applications. All of the aforementioned are fasteners that create mechanical interference between themselves and the tissues being joined.

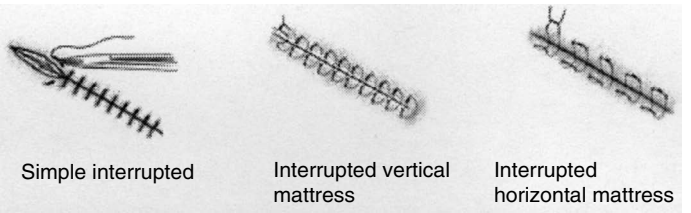

Figure 16.15 Both staples (left) and sutures (right) are used for closing soft tissue during surgery or after trauma. For staples, specially designed staplers are used. (Courtesy of Ethicon Division of Johnson & Johnson, Somerville, NJ, with permission.)

There are also "form-fitting" or "wedging" approaches in orthopedics, as when artificial hip implants are basically jammed into the head of the femur, and may or may not be further bonded using some type of adhesive (see *Adhesive Bonding of Living Tissue*). Some implants encourage tissue ingrowth by producing the implant from a porous form of the material of construction (e.g., by powder processing of a metal or a ceramic), or by texturing the surface to promote cell ingrowth and integration by mechanical locking. This is analogous to integral attachment using designed-in features.

Figure 16.15 shows the use of suturing or stapling in surgery for soft tissue joining. Similarly, mechanical joining using screws and wire or other hardware (like rods or splice plates) is common for hard tissue joining in orthopedics.

Adhesive Bonding of Living Tissue. The idea of using an adhesive to join or rejoin tissue is more recent than the use of mechanical fasteners, especially sutures, but extends back to at least 1787, when it was noted that many workmen glued their wounds closed with solid glues dissolved in water. The use of hide glue (which is similar to gelatin, which is itself derived from collagen protein) was most common, but other biological adhesives such as blood and egg white (albumen) have also been known for centuries.

Beginning in about 1951 with the discovery of methyl 2-cyanoacrylate and then its higher homologs (ethyl, butyl, octyl, etc.), it was found that these monomers polymerized rapidly in the presence of moisture from blood, giving rapid hemastasis. However, despite use in wartime on the battlefields of Korea and, especially, Vietnam, problems of biocompatibility arose, including reports of cancer in laboratory animals. These problems have limited its use to surface applications in oral mucosa (for periodontics) and in life-threatening vascular trauma and the like.

Currently, two principal systems are in clinical use with soft tissues: cyanoacrylate-esters (for limited surface applications, as described above), and fibrin sealants. Fibrin sealants promote a synthetic fibrin clot and produce a wound-covering agent. They have four main advantages: (1) they are hemastatic, (2) they adhere to connective tissue, (3) they promote wound healing, and (4) they are biodegradable. Gelatin–resorcinol–formaldehyde glue developed in the 1960s has been used, but there have been problems with toxicity of the formaldehyde. Newer formulations substitute other aldehydes such as glutaraldehyde and glyoxal, with favorable results.

Table 16.2 Important Properties of Dental Cements and Sealants

	Adhesion Potential (MPa)
Adhesives	
Compound resin	12.3
Adhesive (acrylic) resin	13.1
Polyacid-modified compound resin (PMCR)	14.7
Adhesive (acrylic) resin + activated monomer (ARAM)	19.1
4-META-PMMA	19.1
Cements	
Zinc phosphate cements	5.5
Calcium hydroxide chelate cement	<5.5
Polycarboxylate cements	9.1
Type 1 glass-ionomer cements (GIC)	11.3
Polyalkenoate cements	13.3
Resin-modified GIC	15.4

Reference: *Dental Materials and Their Selection*, 3rd ed., W.J. O'Brien, Ed. Chicago, Quintessence Publishing Co., Inc., 2002, with permission.

The very newest studies have focused on "bioadhesives" involved in cell-to-cell adhesion, adhesion between living and nonliving parts of an organism, and adhesion between an organism and foreign surfaces. Natural adhesives produced by marine organisms such as mussels and barnacles are especially exciting, as both work best in slightly acidic, saline environments much like the human body. The active agent in the mussel's adhesive has been identified as a polyphenolic protein.

For hard calcified tissue (e.g., bone, tooth enamel, and dentin), adhesives have been and continue to be used with success, usually to augment gross mechanical interlocking (e.g., for fillings, crowns, and veneers on teeth and for prostheses on bones). Examples of dental cements include zinc phosphate, zinc polycarboxylate, glass ionomers, various resin sealants, and ceramic-filled resins (see Table 16.2). For bones, similar formulations are used, as well as newer bone powder-filled bioabsorbable cements.

The use of adhesives, along with the use of various mechanical hardware, is common in dental restoration, as shown in Figure 16.16.

"Welding" of Living Tissue. It could be debated whether the use of heat in traditional cauterization and freezing (using cryogenics) for tissue joining are welding analogues or not. They certainly are based on the general definition of welding given early in this book (Chapter 1, Subsection 1.6.4)—the bringing together of materials using the natural forces that arise within those materials to achieve adhesion. The problem is, of course, that welding with either extreme heat, or, in the unusual case of cryogenics, extreme cold (relative to the body's temperature of 37°C (98.6°F) kills the living component of tissue. However, one could argue that this, in turn, would trigger the natural wound healing process and encourage cell growth and remodeling. Perhaps just providing the correct scaffold proteins as a necessary starting "filler" could be considered analogous to welding.

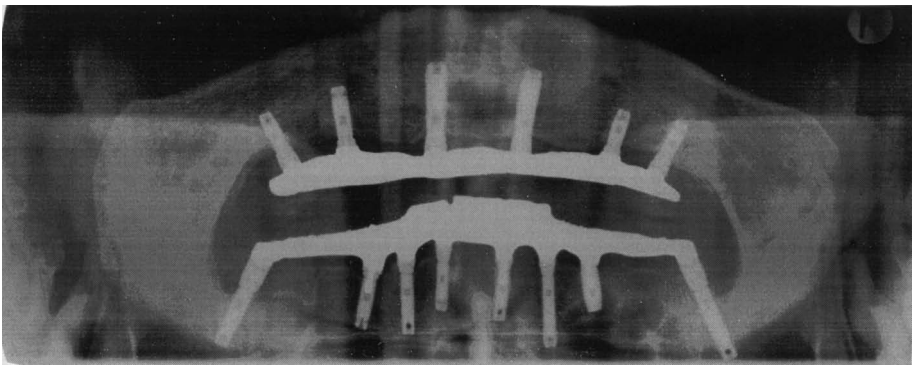

Figure 16.16 Mechanical fasteners, such as screws and wires, and hardware, such as posts and frames, are used for fixating teeth into bone. The use of an elaborate frame with posts is shown here. (Courtesy of John Brunski, Professor, Biomedical Engineering Department, Rensselaer Polytechnic Institute, Troy, NY, with permission.)

Cauterization, which can use rapid heating (through an applied electric current or spark or a laser) or rapid freezing (using a cryogenic probe) causes local blood coagulation, which is the step after injury in the natural wound healing process. Laser and cryogenic procedures used in the reattachment of a detached retina in an eye, for example, at least lead to new tissue growth by properly triggering self-healing.

While seemingly not supportable by solid peer-reviewed papers in the open literature (perhaps because of interest by the military), there have been reports of accelerated mending or rejoining of bone in the presence of applied electromagnetic (or simply electric or magnetic) fields. The alleged, and logical-sounding, mechanism is accelerated ionic transport (an essential part of bone healing) to promote bone healing, purportedly with dramatic shortening of the healing time. To the extent to which this is true, this is clearly more a welding process than anything else.

Figure 16.17 shows a laser being used to reattach a detached retina.

16.4.5 Promoting Biocompatibility at Tissue–Material Implant Interfaces

As stated earlier, most living cells needs to attach to something in order to grow. Cell attachment is necessary for a variety of cell functions, including migration, proliferation, and other cell-specific functions. Many cells are what are called ''attachment-dependent'' in that they will not proliferate, and might die, unless they are adhered to a surface. In order to get full integration of a synthetic material into the body, cells need to be able to attach to it and create more living cells around it. The chemical and physical properties of a material will determine how the body will react. This is referred

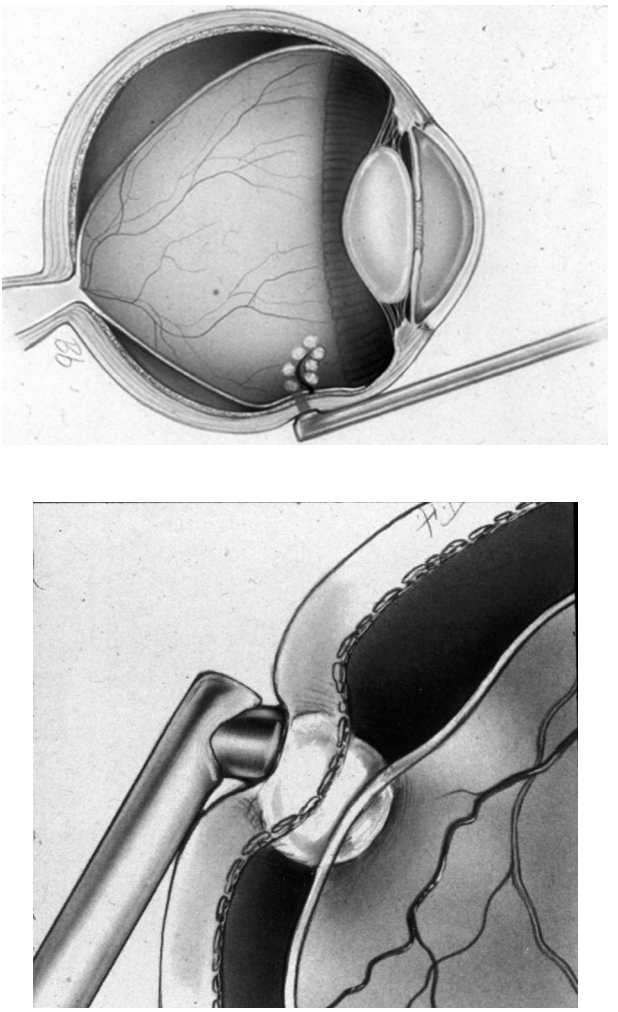

Figure 16.17 In an analog to welding, a laser beam can be used to reattach a detached retina, with the heat of the laser causing joining by coagulating protein. (Courtesy of Julia A. Haller, M.D., The Johns Hopkins Hospital, Baltimore, MD, with permission.)

to as the material's "biocompatibility." The accepted definition of biocompatibility taken from *Definitions in Biomaterials* is "The ability of a material to perform with an appropriate host response in a specific application."[6]

Generally, the best attachment is to produce scaffold proteins (like in the extracellular matrix), but cells will also attach to certain types of treated synthetic surfaces. The general approach to promote attachment is by "preconditioning" or

[6] D.F. Williams, Ed. *Definitions in Biomaterials*. Amsterdam, Elsevier Publishers, "Progress in Biomedical Engineering 4," 1987.

conditioning the surface of the synthetic material. The main goal is to provide a surface that will support the attachment of cells and will induce the appropriate function from those cells. Again, as in wound healing, there is an element of cell signaling that comes from the matrix that the cell is attached to. If the signals are wrong, the function will be wrong. In many cases, the goal is to integrate the material into the existing living tissue, and this is done through the action of the living cells, which need to be able to adhere to the material and function appropriately on or near it.

There are a variety of techniques, still under study and development, for promoting cell attachment through biocompatibility. Adsorption of protein onto a surface is a widely used technique. Depending on the surface, proteins will naturally adsorb and will coat the surface so that cells can adhere.[7] This is, in fact, what happens to many implants immediately after they are put in place in the body. The nature and amount of protein that is adsorbed is important, however, in determining subsequent cell-mediated events. Properties of surfaces that affect their interaction with proteins include (1) surface topography (with greater surface area promoting interaction); (2) composition (with chemical makeup affecting interaction forces); (3) hydrophobicity (with aversion to water tending to favor protein adsorption); (4) heterogeneity (with nonuniformity of surface characteristics tending to promote adsorption); and (5) potential (with surface potential influencing interaction).

Besides overall coating by adsorbed proteins, the surface of a material implant can be micropatterned (using soft lithography) with protein so that cells adhere only in certain areas or in certain patterns. Other preparation techniques intended to alter the potential of the surface employ corona discharge to enhance the bonding of certain proteins.

Newer techniques are being developed to more fully control what proteins are adsorbed and how they are presented on the surface. This is a major thrust of nanotechnology within biotechnology, where it is envisioned that by controlling the nanoscale features of a surface, one will be able to control the conformation of adsorbed proteins and the subsequent biological reactions. Nowhere may the potential for nanotechnology be greater than in tissue engineering.

SUMMARY

Structure, beyond material, is a factor in the selection of one joining process or approach over another. Structural features of importance are size, section thickness, and shape complexity, with extremes posing the greater challenges. Very large sizes force joining to be performed outdoors, on site, which makes control of the environment and manufacturing operations more difficult. Very small sizes challenge the scale of the processing equipment, at least, and may also challenge the process mechanics. Surely, small scales force automation. Very thick and very thin sections also challenge

[7] Such adsorption of protein onto a synthetic material is affected by the protein molecule's size (larger ones having more sites for contact), charge (molecules near their isoelectric point adsorbing more readily), structural stability, and unfolding rate.

processes and processing equipment. Shape complexity tends to challenge labor intensity, joint preparation, and fixturing.

Another major factor is the hostility of the environment within which joining must be accomplished, with key examples of hostile environments being extreme cold (e.g., for welding oil or natural gas pipelines), underwater (e.g., for erection and/or repairing offshore drilling platforms), outer space (e.g., for assembling or repairing orbiting space stations), and radioactive environments (e.g., for performing scheduled or unscheduled maintenance on operating nuclear reactors).

The most complex and elegant structure of all is living tissue, for which joining to other living tissue or to nonliving material implants is of increasing interest and importance in medicine and tissue engineering. For tissue joining, the two keys are providing a suitable protein scaffold and encouraging cell growth. In fact, cells themselves will secrete and remodel scaffold protein. The key to joining living tissue to nonliving material is biocompatibility, promoted by surface conditioning, usually with adsorbed protein.

Living tissue is joined mechanically (e.g., using screws, nails, pins, wire, and hardware in bone repair and sutures and staples in soft tissue repair) or using integral interlocks (e.g., dental implants and hip joint wedging into the head of the femur) and adhesives for soft and hard tissues, as well as analogues of welding (e.g., laser and cryogenic cauterization and field-assisted bone healing).

The future of tissue engineering will evolve as the ability to cause proper joining of living tissue evolves.

QUESTIONS AND PROBLEMS

1. What are the special problems associated with joining very large components into very large structural assemblies? Give problems specific to mechanical joining using fasteners and integral attachments, adhesive bonding, and welding. Give some examples of typical very large structures joined by each of these general approaches.
2. What are the special problems associated with joining very small components into very small assemblies? Give problems specific to mechanical joining using fasteners and integral attachments, adhesive bonding, and welding, brazing, or soldering. Give some examples of typical very small structures joined by each of these approaches.
3. What is meant by the special joining approaches referred to as ''self-joining'' or ''self-assembly''? Why do such approaches make particular sense for creating nano-devices? Suggest some way in which self-assembly would be enabled in a nano-device. Give an example of self-assembly in nature.
4. What are the special problems associated with joining very thick components in general, and by mechanical fastening and welding in particular? Give a typical example of applications with very thick joints, generally greater than 6–8 in. or 150–200 mm thick.

5. What are the special problems associated with joining very thin components into structures? Describe how mechanical joining techniques may still be applicable. Describe how welding may still be applicable. Give some examples of typical situations where very thin components have to be joined, and state how joining is accomplished in each example.
6. What are the special problems associated with joining thin to thick components? Relate your answer to fusion welding and mechanical joining specifically. Give some examples of situations or applications where thin to thick components must be joined, and state how joining is accomplished in each example.
7. What is meant by a "hostile environment" in terms of joining, in general? Give some examples of hostile environments, along with examples of the kinds of objects or structures that have to be joined, and the processes used to accomplish joining in each example. What specific special techniques have to be employed in each example?
8. Briefly discuss what makes joining by fusion welding particularly challenging in each of the following situations:
   a. Joining high-strength, low-alloy steel pipe segments into a pipeline in the Arctic tundra.
   b. Joining high-strength, low-alloy steel pipeline in the scorching, arid desert.
   c. Making a repair on a large bronze ship propeller underwater.
   d. Making an unscheduled repair on a nuclear reactor component during shutdown.
9. What are the special problems associated with joining living tissue? Differentiate between the problems associated with vasculated and non-vasculated tissue and between "soft" and "hard" tissue.
10. Give some examples of specific types of joining used on the following:
    a. Skin
    b. Blood vessels
    c. Cartilage
    d. Bone
    e. Teeth

Bonus Problems:

A. The greatest disaster to ever occur with a nuclear reactor occurred in Chernobyl, Ukraine, when the reactor went into a fault mode and contaminated an area more than 10 kilometers in radius to the point that it is uninhabitable for centuries! To contain the still-smoldering and leaking reactor complex, a huge sarcophagus had to be constructed over acres and acres from concrete and steel. Discuss the complications of accomplishing needed welding and thermal cutting in such a hostile environment.

B. If humans are to ever construct large inhabitable living and working complexes in near-Earth orbits in outer space, it will be necessary to fabricate the basic structural elements *in situ.* One possibility is to roll-form the longitudinal

members of a continuous structural truss with an equal-sided triangular cross-section, to which must be joined pre-fabricated bracing elements. If the entire structure were to be made from thin-gauge Al-alloy, how would you propose to perform joining using an automated or robotic system? Recognize that miles or kilometers of such truss would be needed to erect a really large structure. (Think about the effects of any debris generated, the tremendous accumulation of metal vapor from fusion welding, the power demands, etc.)

C. Give some specific materials used in each of the following joining processes or items for tissue repair:
   1. Surgical sutures
   2. Surgical staples
   3. Soft tissue adhesives
   4. Bone adhesives

D. Look into the process by which cauterization promotes healing in living soft tissue, and draw parallels between the processes of cauterization and welding.

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